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EFFECTS OF DEEP RIPPING ON CHEMICAL AND PHYSICAL PROPERTIES OF A SOLONETZIC SOIL

by

© KENNETH MURRAY RIDDELL

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

SOIL CHEMISTRY

DEPARTMENT OF SOIL SCIENCE

EDMONTON, ALBERTA

SPRING, 1986

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled EFFECTS OF DEEP RIPPING ON CHEMICAL AND PHYSICAL PROPERTIES OF A SOLONETZIC SOIL submitted by KENNETH MURRAY RIDDELL in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE in SOIL CHEMISTRY.

J. R. Webster
.....

Supervisor

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.....

.....

Date April 16, 1986

DEDICATION

This thesis is dedicated to my father, Kenneth Riddell, whose untimely passing took from me my mentor and best friend. His unceasing devotion to our family and to the creation of an egalitarian society will never be forgotten. I salute his efforts and thank him from the bottom of my heart.

ABSTRACT

The use of deep ripping to ameliorate Solonetzic soils is becoming an increasingly popular practice in Alberta. In response to this trend, an experiment was designed to assess the effectiveness of this tillage technique. A detailed investigation into the impact of deep ripping on selected chemical and physical properties of Dark Brown Solodized Solonetz soils (Killam and Daysland soil series) located in east-central Alberta was initiated.

Detailed sampling to test the effects of ripping on soil chemical properties was carried out in the fall of 1982 on two adjacent fields near Halkirk, Alberta. In the north field where ripping was done with a 56 cm shank spacing, sampling was done along the boundary between the check strip and the ripped area. Samples were also taken from a deep plowed strip located on the other side of the check strip. In the south field where ripping was done with a 112 cm shank spacing, sampling was done in the undisturbed area between shank tracks and in the disturbed shank zone. Samples for soil chemical properties were also used for investigating particle size distribution.

Changes in soil moisture in a ripped and unripped soil profile were monitored through the summer of 1983 in the south field (wide shank spacing) where sampling for chemical properties had been done the previous fall. Weekly gravimetric sampling at fixed locations between former sampling pits was used as the method for measuring soil moisture.

Results of the investigation into soil chemistry suggest that ripping has the ability to alter soil chemical properties but not to the extent of that caused by deep plowing. Ripping done with the wide shank spacing (112 cm) appeared to have caused changes in soil chemistry, increasing SAR, EC and pH in upper horizons, through both physical lifting of salts and allowing more moisture into the profile which subsequently altered salt distribution patterns. Similar changes to soil chemistry from ripping done with a narrow shank spacing (56 cm) were not detected.

Results of the investigation into particle size distribution parallel the findings of the soil chemistry inquiry. Ripping with a wide shank spacing (112 cm) caused upward movement of clay from the lowest (Csk) horizon to the second (Bnt) horizon. Ripping with a narrow shank spacing (56 cm) caused very little change to clay distribution in the profile.

Results of the investigation into moisture distribution in ripped and unripped soil profiles of the south field (wide shank spacing) indicate greater moisture penetration between the 15 and 40 cm depths in the ripped profile. The increased moisture found in this depth interval is used by the crop and is thought to be primarily responsible for the increased growth noticeable above the disturbed shank zone.

Detailed investigations into chemical and physical properties of Solonetzic soils altered by ripping have shown that it has the ability to both alter chemical properties and significantly increase moisture penetration. While increased moisture penetration visually

improves crop growth, it also leads to changes in salt distribution which may be deleterious. By breaking down the existing Bnt horizon and allowing moisture to fluctuate freely between the surface and saline subsoil, the potential for resalinization is being realized. This would cause a reversal in the evolution of Solonetzic soils towards zonally normal soils, which would be an undesirable step backwards.

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First and foremost I would like to acknowledge my mother, Kathleen Riddell, for her constant support throughout my studies. Her patience, understanding and words of wisdom will never be forgotten. Thanks mom!

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In addition to the people directly related to the project, I would also like to thank the many friends, both off and on campus, who encouraged me to finish my thesis. Names are too numerous to mention but I thank each and every one of you.

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TABLE OF CONTENTS

	Page
1. INTRODUCTION	1
2. LITERATURE REVIEW	3
2.1 GENESIS OF SOLONETZIC SOILS	3
2.1.1 Areal Extent	3
2.1.2 Salinization	5
2.1.2.1 Salts in till	8
2.1.2.2 Salts in bedrock	8
2.1.3 Solonization	9
2.1.3.1 Sodium	11
2.1.3.2 Clay mineralogy - swelling - dispersion - hydraulic conductivity	12
2.1.3.3 Desalinization - Bnt formation	15
2.1.4 Solodization	19
2.2 TILLAGE AS AN AMELIORATIVE TOOL: TILLAGE - MOISTURE RELATIONS - RIPPING	19
2.2.1 Tillage Moisture Relations - Deep Plowing	23
2.2.2 Influence of Soil Properties on Ripping	25
2.2.3 Factors Influencing Depth of Ripping	29
2.3 EFFECT OF TILLAGE ON REDISTRIBUTION OF SALTS	31
3. MATERIALS AND METHODS	33
3.1 SITE DESCRIPTION	33
3.1.1 Location of Study	33
3.1.2 Soils	33
3.1.3 Surficial Geology	35
3.1.4 Hydrogeology	36
3.2 PLAN OF TILLAGE PLOTS	37
3.3 DEEP RIPPING OPERATIONS	37

Page

3.4 SAMPLING TECHNIQUES 40

3.5 SAMPLE PREPARATION. 46

3.6 SAMPLE ANALYSES 48

3.6.1 Chemical Analyses. 48

3.6.2 Physical Analyses. 50

3.7 MONITORING OF SOIL MOISTURE 50

4. RESULTS AND DISCUSSION 54

4.1 RESULTS (CHEMISTRY) 54

4.1.1 Sodium Adsorption Ratio (SAR). 54

4.1.2 Electrical Conductivity. 67

4.1.3 pH 74

4.2 DISCUSSION (CHEMISTRY). 79

4.2.1 Deep Plowing (North Field) 79

4.2.2 Ripping (North Field). 80

4.2.3 Ripping (South Field). 81

4.3 RESULTS (MOISTURE). 83

4.4 DISCUSSION (MOISTURE) 85

4.5 RESULTS (PARTICLE SIZE DISTRIBUTION). 93

4.6 DISCUSSION (PARTICLE SIZE DISTRIBUTION) 103

5. CONCLUSIONS. 105

6. REFERENCES 108

APPENDIX 114

LIST OF TABLES

		Page
Table 1.	Analysis of variance for SAR, EC and pH data from ripping treatments (North Field)	57
Table 2.	Analysis of variance for SAR, EC and pH data from combined ripping and deep plowing treatments (North Field).	59
Table 3.	Multiple mean comparisons for treatment means for SAR data using least significant difference test (North Field)	60
Table 4.	Ranges, means and standard deviations for SAR values for soil samples from below shank, 20 cm ⟶, check and deep plowed areas (North Field)	61
Table 5.	Analysis of variance for SAR, EC and pH data from ripping treatments (South Field).	64
Table 6.	Multiple mean comparisons for treatment means for SAR data using least significant difference test (South Field)	65
Table 7.	Means, ranges and standard deviations for SAR values for soil samples from check, below shank and 20 cm ⟶ areas (South Field).	66
Table 8.	Electrical conductivity measurements for saturation extracts from samples taken from check, below shank, 20 cm ⟶ and deep plowed areas (North Field)	71
Table 9.	Multiple mean comparisons for treatment means for EC (ms/cm) data using least significant difference test (North Field).	72
Table 10.	Electrical conductivity measurements for saturation extracts from samples taken from check, below shank and 20 cm ⟶ areas (South Field)	73
Table 11.	pH values of soil samples taken from check, below shank, 20 cm ⟶ and deep plowed areas (North Field).	77
Table 12.	pH values of soil samples taken from check, below shank and 20 cm ⟶ areas (South Field)	78
Table 13.	Analysis of variance for moisture data from ripping treatments (South Field).	84

Page

Table 14. Multiple mean comparisons for treatment means for moisture data using least significant difference test (South Field). 85

Table 15. Particle size and available moisture percentage for ripping samples (North Field) 97

Table 16. Particle size and available moisture percentage for ripping samples (South Field) 98

Table 17. Analysis of variance for percent clay data from ripping treatments (South Field). 100

Table 18. Analysis of variance for percent clay data from ripping treatments (North Field). 100

Table 19. Percent clay values for samples taken from below shank, 20 cm ⟶ and check areas (North Field). . . . 101

Table 20. Percent clay values for samples taken from below shank, 20 cm ⟶ and check areas (South Field). . . . 102

LIST OF FIGURES

		Page
Figure 1.	Simplified model of evaporite basin in early stage of development	10
Figure 2.	Shearing planes in different soils cut by a flat inclined blade	27
Figure 3.	Field location of deep ripping plots	34
Figure 4.	Outline of Alberta Agriculture plots located in North Field SW 3-40-16-W4.	38
Figure 5.	Sampling locations for soil chemistry within the check strip, below the shank and 20 cm to one side of the shank (North Field)	44
Figure 6.	Sampling locations within the check strip, below the shank and 20 cm to one side of the shank (South Field).	47
Figure 7.	Diagram outlining sampling procedure for moisture samples taken throughout summer of 1983.	52
Figure 8.	Sodium adsorption ratio (SAR) vs. depth for ripping and deep plowing treatments (North Field).	56
Figure 9.	Sodium adsorption ratio (SAR) vs. depth for ripping treatments (South Field)	63
Figure 10.	Electrical conductivity (EC) vs. depth for ripping and deep plowing treatments (North Field).	68
Figure 11.	Electrical conductivity (EC) vs. depth for ripping treatments (South Field)	69
Figure 12.	pH vs. depth for ripping and deep plowing treatments (North Field)	75
Figure 13.	pH vs. depth for ripping treatments (South Field).	76
Figure 14.	% moisture vs. time, with weekly precipitation data, for ripping treatments at 0-5 cm and 5-10 cm depths.	86
Figure 15.	% moisture vs. time, with weekly precipitation data, for ripping treatments at 10-15 cm and 15-20 cm depths.	88

Page

Figure 16. % moisture vs. time, with weekly precipitation data, for ripping treatments at 20–25 cm and 25–30 cm depths. 90

Figure 17. % moisture vs. time, with weekly precipitation data, for ripping treatments at 30–35 cm and 35–40 cm depths. 92

Figure 18. % clay vs. depth for ripping treatments (North Field) 95

Figure 19. % clay vs. depth for ripping treatments (South Field) 96

LIST OF PLATES

		Page
Plate 1.	Kellough 5000 deep ripper.	39
Plate 2.	Bobcat tractor used to excavate sampling pits. . . .	41
Plate 3.	Disturbed zone where the ripper shank had passed through the soil. Disturbed zone outlined by orange flagging.	42
Plate 4.	Uneven crop growth present in South Field. Greener crop with increased height centered over "below shank" area	94

1. INTRODUCTION

Solonetzic soils occupy approximately four million, three hundred thousand hectares of land in Alberta, which represents 30% of the land under cultivation. Realizing that nearly one-third of the land in production is affected to some degree by the presence of a Bnt horizon, with its undesirable chemical and physical properties, underscores the need for research into ameliorative techniques.

Researchers working in Canada and around the world on similar sodic and saline-sodic soils have investigated the use of tillage techniques (deep plowing and ripping) and chemical amendments (gypsum and lime) to ameliorate these soils. In Alberta, extensive work has been done to assess the merits of deep plowing as a method for improving Solonetzic soils. Very little investigation has been done to evaluate the effectiveness of ripping as an ameliorative tool. This is quite ironic because prohibitive costs associated with deep plowing have forced many farmers around the Province to consider using ripping as an alternative to deep plowing.

In response to the increased use of ripping a study was designed to test its usefulness as a tool for ameliorating Solonetzic soils. Specific objectives of the study were:

(1) To assess the effects of ripping on changes in soil chemical properties, such as electrical conductivity (EC), sodium adsorption ratio (SAR) and pH.

(2) To compare the effect of shank spacings on changes in soil chemistry.

(3) To determine moisture distribution patterns over the growing season in a ripped and unripped soil profile.

To this end, a study site was selected with valuable advice from John Hermans, Director of Soil Conservation, Alberta Agriculture, and the results of the investigation are reported herein.

2. LITERATURE REVIEW

2.1 GENESIS OF SOLONETZIC SOILS

Solonetzic soils found in Western Canada have evolved over a period of approximately ten thousand years. After the most recent glaciation, these soils began to develop in areas influenced by saline groundwater and/or saline bedrock. Solonetzic genesis leads to the emergence of a diagnostic Bnt horizon.

Typical features of this horizon are a columnar-prismatic macrostructure, blocky mesostructure, dark staining on the peds, and a very hard consistency when dry. The ratio of calcium to sodium on the exchange complex must be ten to one or less (Can. Soil Survey Comm. 1978). The value of ten should not be taken as a constant, however, but rather as a general coefficient, because, characteristically features of Bnt horizons have been shown to develop at ratios of higher than ten to one (Harron 1979).

2.1.1 Areal Extent

The genesis of Solonetzic-type soils has been studied extensively in many countries throughout the world. Solonetz and solonetz-like soils occur throughout Europe, and occupy over 20 million hectares throughout Bulgaria, Czechoslovakia, France, Hungary, Romania, Spain, European U.S.S.R., and Yugoslavia (Szabolcs 1971). In the U.S.S.R. proper, it has been estimated that there are around 100 million hectares of land affected by some degree of solonetzicity (Pak 1971).

On the North American continent, there are about 2.6 million hectares of solonetz-type land in the United States and 7.0 million hectares of solonetz-type land in Canada (Szabolcs 1979). Within Canada, Solonetzic soils are found predominantly on the prairies. There are about 4.3 million hectares of Solonetzic soils in Alberta (Alberta Agriculture 1981) and 1.5 million hectares where Solonetzic soils are dominant in Saskatchewan (Anderson and Ballantyne 1982). On a percentage basis, Solonetzic soils occupy 30% of the arable land in Alberta. The prevalence of this type of soil in these areas underscores the need to understand the development of, and ameliorative techniques applicable to, such soils.

Research as to the origin of Solonetzic soils dates back to the turn of the twentieth century. Working in the early nineteen hundreds, researchers such as Hilgard, Gedroits, Glinka, Kelly, Vil'yams, and de Sigmond initiated experiments to explain their respective theories concerning Solonetzic soil evolution. The knowledge gained from these investigations still stands today as a base for studying Solonetzic soil (Landsburg 1981).

The three processes involved in the development of Solonetzic soils are salinization, solonization, and solodization. Salinization and solonization are essential for the development of a Bnt horizon. Solodization represents an advanced evolutionary stage, not considered necessary for Solonetzic development.

2.1.2 Salinization

The process of salinization involves the accumulation of soluble salts at or near the landscape surface (Pawluk 1982). Mechanisms by which salinization takes place are varied. The most common, and frequently dealt with, scenario concerns the transfer of soluble salts via groundwater flow. Solonetzic development in Western Canada is closely related to groundwater flow.

Another mechanism for salinization involves the concentration of surface salts by evaporation of salt-containing water bodies. In unglaciated areas of the world, characterized by former marine environments, this would be an important process. A third possible mechanism for salinization involves geologic processes which result in the lifting or uncovering of saline parent material at the surface. In glaciated areas, saline bedrock can be thrust to the surface in an area otherwise dominated by non-saline tills. In an erosion environment, saline parent material previously unexposed to the surface can be uncovered by the forces of wind, water and gravity. These geologic processes would be important in areas where saline parent material is covered by thin layers of overburden, as is the case in parts of Western Canada.

As previously mentioned, groundwater is thought to play an integral role in the genesis of Solonetzic soils in Western Canada. After the most recent Wisconsin glaciation, some ten thousand years ago, regional groundwater flow originating as glacial meltwater in the Rocky Mountains salinized many parts of the prairies (Pawluk 1978). Regional groundwater moved eastward as a confined flow

through deep, permeable beds, dissolving mainly sodium salts from marine and brackish water sediments, and discharging these at points adjacent to the Canadian Shield (Pawluk 1982). Sporadic discharge occurred as a result of the upward leakage of eastward-moving water through cracks, fissures and faults in the heterogeneous, overlying geologic strata.

In areas where surficial glacial drift was thin, and local relief was not substantial, regional flow dominated and substantial salinization resulted. In areas of thicker glacial drift, with marked local relief, there was a superimposition of substantial local and intermediate groundwater systems on the upward-leaking regional system. Salinization was limited to local discharge in these areas.

The extent to which deep regional groundwater and shallower groundwater passing over or through shallow bedrock have combined to cause salinization is still being debated (Maclean and Pawluk 1975). The idea that ascending artesian waters play a role in salinization in other parts of the world has also been advanced by Kovda, a Russian scientist. Kovda and Samoilova (1969) state that:

> "in areas of regional faults and geosynclines along the periphery of mountainous folded districts, in the zones of tectonical fractures the inflow of deep pressure waters may be very considerable and may determine many soil geochemical peculiarities of the territory. It may be especially well-pronounced in the arid climate, due to an intensive evaporation favoring the formation and accumulation of salt minerals from the solutions brought by deep water ..."

Kovda also suggested the significance of deep sodium-hydrocarbonate waters, desulfurized via sulfate reduction and formed in association

with oil and gas deposits, as an important factor in the spread of salinity. This theory would seem very relevant to the Alberta situation.

In addition to groundwater, there are other important aspects of the hydrological cycle which must be considered when dealing with salinization. Two key factors are precipitation and evapotranspiration. Accumulation of salts is favored during warm dry periods when evapotranspiration removes water and concentrates salts at the surface. Reduced precipitation at such times prevents leaching of the gathering salts.

Research into paleoclimates during the Holocene epoch indicates the occurrence of a warmer, drier period, termed an Altithermal, between the years 8450 and 4680 B.P. Specific research on post-glacial climates in Alberta, using molluscs as climatic indicators, has determined that a warmer climatic interlude occurred between the years 9000 and 7000 B.P. (Harris and Pip 1973). This warmer climate must have enhanced salinization on a broad scale across the prairies.

Having considered broadly based concepts related to salinization, such as groundwater and climate, a more detailed examination of the salts involved is in order. The combination of potassium, sodium, calcium and magnesium sulfates, bicarbonates, and chlorides existing in the salinized profile will exert a great degree of control over the future genesis of a solonchak (Joffe 1948). In further considering salts and salt combinations, the interactions between specific ions and the mineral and organic matter present in the soil must be taken into account.

2.1.2.1 Salts in till

Non-salinized glacial drift and lacustrine parent material in Western Canada originally contained one to three percent calcium and magnesium carbonate (Bowser et al. 1962). Investigations into calcium oxide contents of Alberta tills have revealed a close correlation between areas with high calcium oxide tills and areas of Chernozemic soils in central and southern regions of the province (Pawluk and Bayrock 1969). Solonetzic soils tend to develop on tills that have accumulated soluble salts after their deposition. An analysis of the water soluble salts in Alberta tills revealed that sodium sulfate was the principal salt in these soils (Pawluk and Bayrock 1969). Sodium sulfate has been shown to be the predominant salt influencing the development of Canadian Solonetzic soils (Cairns and Szabolcs 1973). Till areas containing large amounts of soluble salts do not coincide with specific bedrock formations but rather are related to groundwater discharge.

2.1.2.2 Salts in bedrock

Bedrock formations underlying the prairie portion of Alberta are predominantly of upper Cretaceous age. Cretaceous deposits are composed primarily of shale, sandstone, conglomerate carbonates, coal and evaporates (Clayton et al. 1977). Bentonitic clays are frequently found as separate deposits or as cementing agents in sandstone. Formations of marine or brackish water origin, such as the Edmonton and Bearspaw groups, are usually quite salty (Bowser et al. 1962). Lying below the Cretaceous aged bedrock is the Elk Point

Formation of middle Devonian age. This formation contains deposits of evaporitic salts (Hamilton 1971). Evaporite salts are formed by precipitation from sea water and subsequent evaporation in basins partially or wholly cut off from the ocean (Hamilton 1971). A simplified model of an evaporite basin in its early stages of development is presented (Figure 1 from Hamilton 1971).

Evaporation concentrates dissolved salt near the surface, causing the formation of dense brines which settle to the basin bottom. As these brines become more saline, salts precipitate according to their solubility products. Calcium carbonate and calcium sulfate precipitate first, followed by sodium chloride and finally magnesium and potassium salts (Hamilton 1971). The relatively soluble sodium chloride salts are easily redissolved and transported by regional groundwater to salinize areas of regional discharge.

2.1.3 Solonization

The next stage in the genesis of Solonetzic soils is titled 'solonization'. During this period, the salinized profile undergoes radical transformations leading to the development of a Bnt horizon. In order for solonization to take place, two preconditions must be met. First, salinization must have resulted in accumulations of significant amounts of sodium ions and, secondly, there must have been adequate amounts of expandible clay minerals present (Pawluk 1982). Once these prerequisites are satisfied, a gradual reduction of salts in the profile, caused by environmental changes, is required for solonization to proceed (Pawluk 1982).

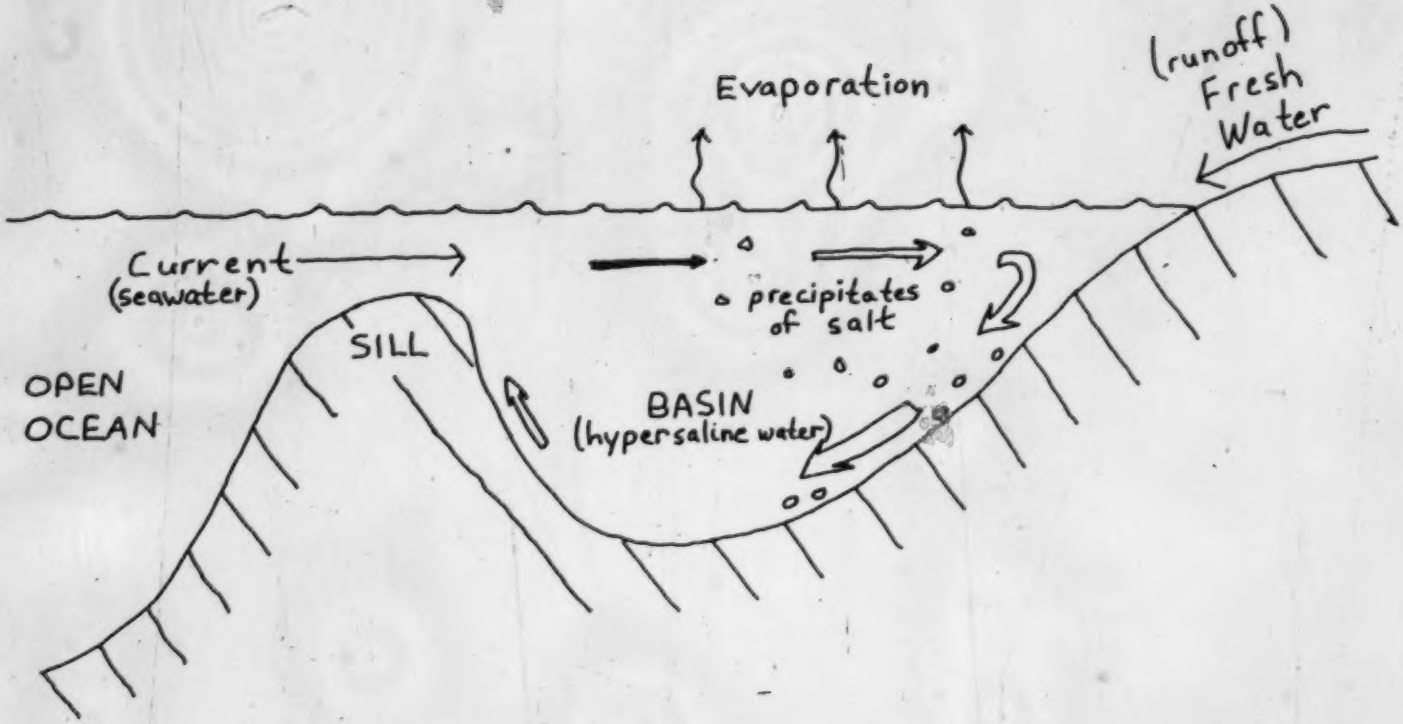


Figure 1. Simplified model of evaporite basin in early stage of development (after Hamilton 1971).

2.1.3.1 Sodium

The extent to which sodium must be present in solution and on the exchange complex prior to solonization is controversial. Laboratory experiments dealing with desalinization of artificially salinized soils in the Soviet Union have led to claims that Solonetzic development occurs only in cases of extreme prevalence of neutral salts of sodium in solonchak composition (90% sodium salts out of total salts) (Tyurin 1960).

In neutral soil solutions, dominated by chloride and sulfate anions, the extent to which alkaline earth cations are rendered inactive by ion pairing and complex ion formation is greatly reduced over alkaline soda solutions. Consequently, small adjustments in the ratio of bivalent calcium and magnesium ions to monovalent sodium ions in solution can result in dramatic changes on the exchange complex due to the preferential adsorption of bivalent cations.

Soviet literature places a great deal of emphasis on the need for sodium to be adsorbed from alkaline soda solutions ($NaHCO_3$ and Na_2CO_3) in Solonetzic development (Tyurin 1960). The presence of carbonate is said to paralyze the desorption effects of bivalent cations and allows sodium to remain on the exchange complex. However, research done in Western Canada suggests that sodium carbonate has not played a significant role in developing Solonetzic soils (Cairns and Szabolcs 1973).

Rather than sodium carbonate, sodium sulfate is seen to be the dominant salt influencing Solonetzic soil in Canada (Cairns and Szabolcs 1973). Although sulfate is not as effective at complexing

or precipitating bivalent cations as is carbonate, research done by Alzubaidi and Webster (1983) showed that substantial amounts of calcium can be rendered inactive by its presence. Forty percent of the total calcium present in saturation extracts from Bnt horizons was shown to be neutralized as calcium-sulfate ion pairs (Alzubaidi and Webster 1983). In contrast, only 3.3% of the sodium existed as sodium-sulfate ion pairs in the saturation extracts. Sulfate, as well, has the ability to reduce the desorptive effects of calcium.

2.1.3.2 Clay mineralogy - swelling - dispersion - hydraulic conductivity

The need for significant amounts of expandible clay minerals arises from the role of these minerals in reducing hydraulic conductivity and restricting movement of colloidal material. Soils containing high percentages of montmorillonite in their clay mineral suite are subject to greater reductions in hydraulic conductivity under low salt, high sodium conditions than are soils high in kaolinite or non-expandible 2:1 layer silicates (McNeal and Coleman 1966a).

The authors of the above statement attribute the greater decline in hydraulic conductivity of montmorillonitic soils to "closing of conducting pores by *in situ* mineral swelling" (McNeal and Coleman 1966b). Subscribers to the "domain" model, McNeal and Coleman claim that swelling begins with interlayer expansion within a coherent gel structure. Under high sodium, low electrolyte conditions, solution initially moves into spacings between individual clay platelets, thus forcing them to expand. A comparison of the c-axis spacing of Ca-

saturated montmorillonite (19 Å) to that of a sodium saturated domain at a salt concentration of 12.5 meq.L^{-1} (122 Å) reveals the magnitude of the difference in expansion of the two systems (McNeal and Coleman 1966b).

The expansion of interlayer regions between platelets causes individual clay particles to swell. This process, in turn, causes the swelling of packets of clay formed as solid particles. As the solid particles swell, the amount of interparticle space within the gel increases and more solution begins to be taken up by the gel structure. As the extent of interlayer swelling increases, the amount of solution occupying interstitial locations increases with respect to interlayer solution.

In contrast to the theory that hydraulic conductivity reductions are initiated by interlayer swelling is a view based on the concept of tactoid integrity at varying levels of sodium saturation. A tactoid can be described as a discrete entity consisting of 4-9 clay platelets arranged in a parallel fashion (Frenkel et al. 1978). When montmorillonite is saturated with calcium, the individual clay platelets are tightly packed (9 A spacing) and the tactoids maintain their integrity.

As sodium is gradually added to calcium saturated montmorillonite under low electrolyte conditions, sodium is adsorbed onto the external edges of the tactoid, thereby leading to the development of a more diffuse double layer. The interlayer region between clay platelets remains dominated by calcium, and only the areas surrounding the tactoid develop an expanding layer. Depending on

electrolyte concentrations, diffuse double layers between tactoids begin to overlap and repel each other. Consequently, tactoids disperse, but little or no interlayer swelling occurs.

As concentrations of sodium relative to calcium increase (exchangeable sodium percentage greater than 25), sodium ions begin to replace calcium on interlayer positions (Frenkel et al. 1978). This facilitates the development of diffuse double layers on interlayer surfaces and causes interlayer repulsion. This process, in turn, causes swelling which exerts pressure on the structural integrity of individual tactoids. At an exchangeable sodium percentage of 50, internal pressure of interlayer swelling causes complete deterioration of tactoid structure (Frenkel et al. 1978).

In accordance with the theory of tactoid integrity, it is assumed that tactoid dispersion precedes interlayer swelling at exchangeable sodium percentages of less than 25. This means that the importance of expandible clay minerals in causing reductions in hydraulic conductivity is somewhat reduced. Research has shown that kaolinite, which does not have the capability for interlayer swelling, is susceptible to dispersion at above neutral pH and can cause significant reductions in hydraulic conductivity under low electrolyte, fresh water conditions (Frenkel et al. 1978). Therefore, it may be concluded that expandible clay minerals play a major role in reducing hydraulic conductivity under low salt, high sodium conditions, but that non-expandible clays are not to be seen as unimportant. Dispersion and particle translocation are seen as the dominant mechanisms underlying hydraulic conductivity decreases

in coarse textured soils. Swelling, on the other hand, is viewed as the dominant mechanism in soils containing significant amounts of expandible minerals and in compact, confined soils where swelling prevents any dispersed particle movement (McNeal and Coleman 1966b).

2.1.3.3 Desalinization - Bnt formation

Given a soil profile salinized with adequate amounts of sodium, and containing significant amounts of expandible clay minerals, the next step in solonization is desalinization. Throughout the prairies of Western Canada, desalinization has involved the removal of salts through increased precipitation and the development of integrated drainage systems (Pawluk 1982).

Increased precipitation following the Altithermal resulted in a phenomenon whereby areas that had previously experienced a net upward flux of salt and water, from a capillary fringe maintained by high evapotranspiration, became net leaching areas (Pawluk 1982). As a consequence of the development of integrated drainage systems, post-glacial meltwaters began to downcut pre-existing channels and cut out new channels. Former discharge areas became recharge areas as newer and deeper drainage channels acted as synclines to alter drainage patterns.

With the onset of desalinization, there is a net lowering of electrolyte content in pore solutions. Reductions in salt concentration in bulk solution allow the expansion of the sodium influenced diffuse double layer surrounding soil colloids. As the envelope of cations surrounding negatively charged colloids thickens,

expansion is restricted by interaction with double layers on adjacent soil colloids.

The overlapping of double layers leads to repulsion and the subsequent dispersion of the colloids. The extent of dispersion will vary, depending on the exact levels of exchangeable sodium and electrolyte concentration. Common threshold figures for the origin of dispersion are a total salt content of 0.10-0.15% or less, and an exchangeable sodium percentage of at least 10-15% (de Sigmond 1926).

Once dispersion has occurred, formerly stable aggregates are broken down into minute clay fragments, which are susceptible to downward movement in the profile. However, the extent to which downward movement actually occurs is restricted because, as previously discussed, hydraulic conductivity is severely limited by the swelling of expandible clay minerals and by the clogging of pores by dispersed particles. Hence, dispersed clay accumulates and the development of a slowly permeable Bnt horizon begins.

After initial desalinization, alternating processes of resalinization and desalinization in the solum continue in response to cyclical changes in evapotranspiration and precipitation (Pawluk 1982). An upward flux of sodium salts from the capillary fringe along fine pores in response to matric potential gradients allows for resalinization.

Climatic conditions, such as warm, dry, or prolonged freezing periods, and plant removal of water by transpiration are responsible for creating the upward potential gradients. During periods of rainfall and snowmelt, downward leaching of excess salts through

coarse pores allows for repeated desalinizations (Pawluk 1982). Downward leaching is controlled by gravitational potential gradients. These processes continue to operate as long as there are no more long-term climatological changes and water table depth is maintained at an adequate level to ensure the capillary fringe does not reach the soil solum.

Without the continual regeneration of sodium, a strong tendency would exist for the calcium which is present in the solum, or recycled through plant material, to displace exchangeable sodium on clays that are also subject to alkaline hydrolysis.

1) $Na\text{-clay} + H_2O \rightleftharpoons H\text{-clay} + Na^+ + OH^-$

2) $OH^- + CO_2 \rightleftharpoons HCO_3^-$ (after Pawluk 1982)

Repeated salinization, by mobile sodium and bicarbonate ions supplied through capillary rise, pushes the above reactions to the left and supplies sodium to compete with the calcium being cycled through plants. This perpetuates the dispersed state of the clays and allows for the continued repetition of hydrolysis of sodium clays.

During periods of desalinization, the above reactions go to completion, without reversal, and thus result in alkaline conditions. With the increase in pH, sodium dominated organic matter peptizes readily to form mobile sodium humates, which are leached into the forming clay pan. Once stabilized, the organic substances coat the outer surfaces of dispersed clay particles and impart a blackish-brown color to the Bnt horizon then under formation.

Following numerous cycles of wetting and drying, desalinization and salinization, a densely packed, sticky, clay pan horizon develops near the surface. This emerging Bnt horizon causes a lithologic discontinuity to develop in the upper part of the profile. Small pores dominate the Bnt horizon due to its enrichment in dispersed clays and to its compact nature. The surface horizon(s), on the other hand, is/are depleted of clay and much less compact, yielding larger pore sizes. As a result of this discontinuity, sodium ions rising from the capillary fringe are no longer able to reach surface horizons. Similarly, precipitation and snowmelt entering surface horizons are unable to move through the slowly permeable Bnt horizon. Preventing sodium ions from resalinizing the surface horizon allows alkaline hydrolysis reactions to proceed to completion, thus causing a mild alkalization (Pawluk 1982). Hydrogen ions replacing sodium ions are replaced first by aluminum-hydroxyl ions and, eventually, by calcium and magnesium ions supplied through biocycling.

Concurrent with the foregoing processes is the development of perched water tables on top of the Bnt during wet periods. This latter process provides ideal conditions for intense chemical weathering in regions above, and immediately on top of, the Bnt horizon. Consequently, the pH of the surface horizon becomes acidic and, ultimately, an eluvial Ae horizon may develop. Soluble weathering products are moved into the Bnt through coarse pores. At this point formation of the Bnt horizon is complete and the Solonetzic profile has become well established.

2.1.4 Solodization

The third and final phase of Solonetzic soil development is known as solodization. In order to reach this level of development, the hydrological character of the profile must be altered so that groundwater no longer influences the solum. This is usually accomplished by the lowering of the water table to a depth that prevents the capillary fringe from reaching the Bnt horizon. According to Pawluk (1982), soils described by the terms "Solodized Solonetz" and "Solod" should both fall into this category.

Eliminating the recharge of sodium into the Bnt allows alkaline hydrolysis of sodium clays to proceed without reversal. The cyclical process of "repetitive hydrolysis of sodium clay greatly diminishes as a pedogenic force" (Pawluk 1982). Instead, the surface horizons become more suitable for plant growth, and the biological additions of calcium and organic matter assume greater importance. Roots begin to penetrate the Bnt horizon and circulate calcium, as well as other bases, from the salt enriched lower horizons to the surface (Pawluk and Dumanski 1969). As vegetation continues to flourish, considerable organic matter is added to the surface and the profile begins to approach that of a "zonally normal" soil.

2.2 TILLAGE AS AN AMELIORATIVE TOOL: TILLAGE - MOISTURE RELATIONS - RIPPING

Subsoiling is defined as "the working of soil deeper than ordinary plowing without bringing subsoil material to the surface" (Duley 1957). Another term frequently used to describe subsoiling is

'ripping'. Both terms convey similar meanings, but for the sake of clarity and consistency, the term ripping will be used throughout this review.

A summary of the literature reveals that ripping has been used in many places around the world, including Canada, the United States, the U.S.S.R., Israel, Bulgaria, and Yugoslavia (Obrejanu 1970; Szabolcs 1971; Cairns and Lavado 1981; Henderson et al. 1981; White et al. 1981). Most of the work done in Canada, the U.S.S.R. and Europe has been associated with attempts to ameliorate salt-affected soils, whereas research in the United States has been aimed at using ripping to improve soil moisture conservation in both salt-affected and non-saline claypan soils.

In a review article, the history of subsoiling research in the United States was traced back to the 1890's (Duley 1957). In Canada, ripping research was originated in the early 1970's in various parts of central Alberta (John Hermans 1982 personal communication). Research on ripping in the U.S.S.R. dates back to the mid-1930's (Tyurin 1967). As pointed out in the article by Duley, research has been carried out for some time and has generated both positive and negative results.

Conventional wisdom would suggest that ripping would increase moisture penetration by virtue of crack, fracture and fissure formation. Hydraulic conductivity would be controlled by flow through large, continuous macropores rather than through the assortment of small micropores and discontinuous macropores associated with dense, compact horizons. Saveson and Lund (1958)

inferred increased infiltration was due to a greater proportion of large pores and a greater permeability in saturated soil cores taken from disturbed subsoil layers compared to undisturbed layers (Allmaras et al. 1977).

Research done in the United States by several workers has demonstrated increased water intake rate and soil moisture storage from the use of ripping on slowly permeable claypan soils (Saveson and Lund 1958; Hauser and Taylor 1964; White and Gardner 1981). In each case it was noted that moisture penetrated rapidly in the narrow area opened by the ripper shank.

Hauser and Taylor (1964) studied moisture redistribution around a vertically mulched shank track in a Pullman clay loam soil and noted that the wetting front had reached the depth of ripping (60 cm) in the shank track after only five minutes. Preliminary research into ripping with a vertical mulch at Purdue University showed similar results (Spain and McCure 1956). Moisture redistribution in the fractured areas around the shank track occurred over longer periods of time.

Research done in Hungary showed that ripping to a depth of 60 cm increased moisture penetration between the 20 to 60 cm depths in the treated areas as compared to the check areas (Abraham and Bocksoi 1971). Regarding the permanency of this effect, Hauser and Taylor suggest that visual observation via trenching reveals that physical disruption is still evident after three years. The study done by White et al. (1981) showed that soil moisture relations were improved in ripped areas four years after ripping and the authors claimed long-term eventual success.

Soviet researchers claim that the residual effects of ripping last four years, after which tillage must be repeated (Obrejanu 1970). Work completed in Hungary on deep ripping in combination with lime and gypsum injection concluded that successful reclamation of meadow Solonetz soils was possible, based on a repetition of the process after four years (Bocskai 1974). An important point to remember concerning the work done in the United States is that non-sodic soils were under investigation and, hence, did not require chemical amelioration for long lasting results.

Negative effects on soil moisture conditions as a result of ripping have also been reported in the literature. A review article dealing with the history of subsoiling research cites studies undertaken in the early part of the century which showed that ripping had no positive effects on soil moisture or crop yields (Duley 1957). However, the author also offers that:

> "... a reasonable amount of subsoiling has been done by farmers during the last ten to fifteen years. Many have reported advantages from the practice in the increase in intake of water, particularly during the first year of treatment." (Duley 1957).

Hanks and Thorpe (1956) noted that ripping caused no increase in moisture intake or storage and that, after one year, the soil above the ripper mark was compact and difficult to dig. The 'permanency' of ripping is thus questioned. Research done in Lebanon, using an Arab plow on claypan soils showed no increase in water intake (Henderson et al. 1981).

In Alberta, a comparison of infiltration rates into surface horizons of a ripped and adjacent unripped Brown Solonetz soil revealed that water movement was slowed in the four ripped treatment areas (Cairns and Lavado 1981). However, the authors pointed out that this occurred only at a single site and offered no explanation for the apparent reduction in moisture movement. In general, it may be concluded that there still exists a substantial degree of controversy in the literature regarding the relationship between ripping and soil moisture.

2.2.1 Tillage Moisture Relations - Deep Plowing

In addition to ripping, there is also a great deal of information in the literature on the effects of other forms of deep tillage on soil moisture relations. Deep plowing, using both single bottom and top soil saving plows, backhoes and trenching devices, and large discs are other forms of tillage treatment that have been studied. As in the case of ripping, several authors have reported increased water intake, increased permeability and increased moisture storage in both Solonetzic and claypan soils that have undergone profile modification (Mech et al. 1967; Rasmussen et al. 1972; Musick and Dusek 1975; Musick et al. 1981). Reasons offered for the more favorable regime include increased non-capillary porosity as compared to capillary porosity, and improved air and water permeability.

A long-term study conducted over a 14-year period indicated that the permeability of a dense, compact B2t horizon in an irrigated Pullman clayloam soil was permanently increased by deep moldboard

plowing (Musick et al. 1981). However, the authors noted that maintenance of this long-term residual increase in subsurface permeability was dependent on the continual loosening of surface layers with moldboard plowing.

The deep plowing of a Black Solonetzic soil in central Alberta led to greater infiltration rates and greater water extraction by alfalfa (Bowser and Cairns 1967). Throughout the literature the 'permanency' of alterations caused by deep plowing has not been questioned.

Infiltration tests carried out using a double ring infiltrometer on conventionally plowed (15 cm depth) and deep, moldboard plowed (90 cm) claypan soil in eastern Washington State revealed a significantly reduced infiltration rate on the deep plowed sites (Mech et al. 1967). In relation to the question of deep plowing, it is important to consider the resultant particle size distribution of the mixed profile to prevent crusting. High clay contents and low organic matter levels in the surface of deep plowed soils can cause crusting problems under heavy rainfall and flood conditions.

An overall assessment of experiments performed on ripping and deep plowing reveals the adherence by researchers to a common investigative approach. In general, the tillage was performed on a selected number of sites. Soil conditions were then monitored, through detailed chemical and physical analyses, over a three to five year period. Commenting on this tendency, Rasmussen and McNeal (1973) noted that "such large-scale tests are costly, time consuming and often yield little fundamental information of use in extending results to other soils".

In an attempt to improve on this approach, the above-mentioned authors attempted to predict the relative hydraulic conductivity of a mixed soil profile using a mathematical model. The procedure involved the development of a weighted relative hydraulic conductivity, based on high and low salt solutions, for each horizon in the profile which was to be mixed. The relative hydraulic conductivity for the mixed profile was then predicted, using a summation formula that took into account the depth of each layer, the relative hydraulic conductivity of each layer, and the depth of mixing (Rasmussen and McNeal 1973). Computer modelling, using parameters such as clay content and lime content, was designed to evaluate the feasibility of chemical and physical amelioration of Solonetzic soils. This approach offers an attractive alternative as well as an effective complement to the extensive fieldwork that still needs to be done in this area.

2.2.2 Influence of Soil Properties on Ripping

As was previously stated, the effectiveness of ripping as an ameliorative tool depends on the extent of shattering caused in the subsoil. In situations such as those involving Solonetzic soils, where it is desirable to mix the subsoil with blanketing layers, the amount of lifting and inversion caused by ripping becomes important. The extent to which shattering and lifting occurs as a result of ripping is controlled by several soil properties. These include particle size, colloidal content, organic matter, bulk density, structure, consistency, and chemical composition of colloids (Cooper

1971). In addition to soil properties, other factors such as implement design, depth of tillage, number of operations, and direction of operations are also important. Furthermore, it is very important to consider the subsequent effects of climatic, biologic, and traffic forces acting after the initial disturbance has taken place (Nichols and Reaves 1958).

A demonstration of the influence of bulk density, soil texture, and moisture content on soil shear planes is provided (Figure 2). The soil is first compressed, due to the force applied by the implement and to its own resistance to motion. Following compression, shearing results as a direct consequence of the compressive forces. Although the flat inclined blade does not simulate a ripper shank, the diagram does highlight the effects of these common soil properties on tillage dynamics.

Most ripping for experimental purposes has been done in the fall on recently harvested fields in order to take advantage of dry soil profile conditions. A common recommendation for soils with substantial amounts of clay is that ripping should not be done unless soil moisture content is below the plastic limit (Nichols and Reaves 1958). Plastic limit is defined as the moisture content at which the soil is "sufficiently moist to form a small ball and sufficiently plastic to roll out like a wire" (Nichols and Reaves 1958). Problems arising from excessive moisture in soils are associated with the occurrence of compaction, while problems arising from excessive dryness of the soil are evident in the presence of large clods that are difficult to cultivate.

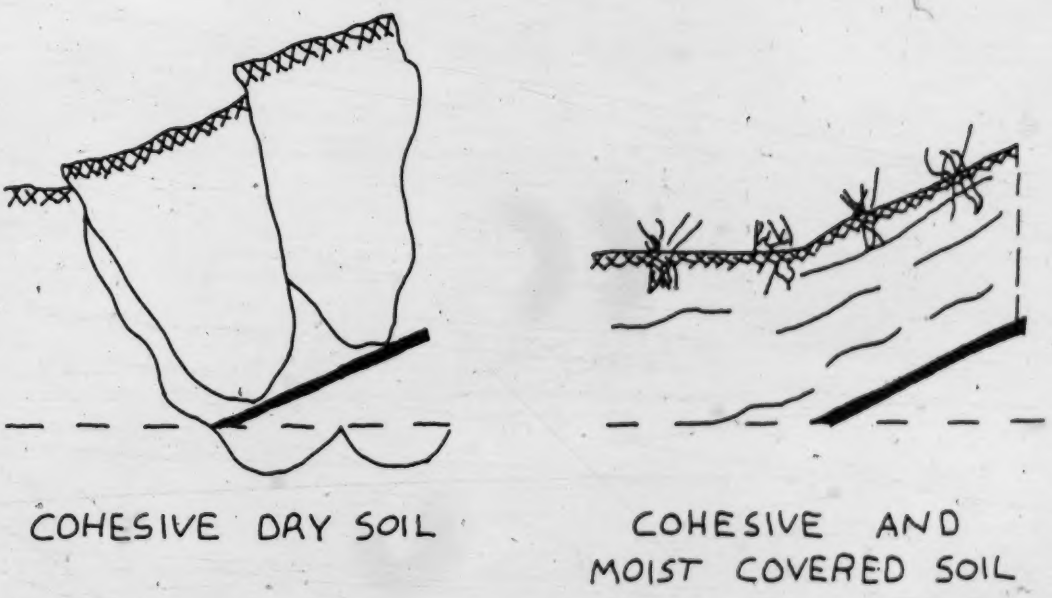


Figure 2. Shearing planes in different soils cut by a flat inclined blade (after Cooper 1971).

A certain degree of controversy exists in the literature regarding moisture content-tillage relationships for ripping. Results of extensive ripping research done in Hawaii on a silty clay soil (low humic Latosol) have demonstrated that mean thickness of soil loosened was not altered substantially whether tillage was done at near wilting point or near field capacity (Trouse and Humbert 1959). At all moisture contents, plastic flow shear occurred below the zone of shear plane development, thus causing the walls on vertical grooves to be compressed to a higher bulk density. In the case of very moist soils, Trouse and Humbert (1959) have suggested that shear plane development is much more shallow.

One advantage of ripping at high moisture contents is the corresponding reduction in power required to undertake the procedure. Research has demonstrated the occurrence of significant reductions in energy requirements for deep tillage of clay loam and clay soils at high moisture contents (Hadas et al. 1978). In addition, the moister soils break down into smaller aggregates with less energy input (Hadas et al. 1978). In short, it would appear that in selecting the optimum moisture content for ripping, the factors of compaction hazard, depth of shear plane development, and power requirements must all be considered.

A further complication affecting the merits of ripping arises from the time-consuming nature of this operation. This means that in the event of a highly variable climate, the likelihood of completing the procedure under ideal conditions is reduced. Estimates of working capacity for ripping range from 0.37 ha hr^{-1} to 1.19 ha hr^{-1},

depending on speed, depth of operation and soil conditions (Aleksandrian 1980; Drever and Wiens 1980).

2.2.3 Factors Influencing Depth of Ripping

The depth of operation and the number of operations to be done are two other variables which have commanded the attention of farmers and researchers alike. The depth of operation is dependent on the size of tractor available, the number of shanks on the ripper, and the shape of the ripper standard. While the tillage depth must be sufficient to facilitate penetration of the target horizon, a number of factors may potentially limit the achievement of this goal. Power requirements increase substantially with tillage depth. Cooper (1971) reported that doubling the depth of operation from 28 cm to 50 cm increased the draft requirement four-fold to 1900 kg.

Another important factor affecting the depth of operation concerns the curvature of the standard (shank) carrying the ripper teeth. Curved standards cause a significant reduction in draft (Nichols and Reaves 1958). In the case of a curved standard, the ripper teeth are located in front of the standard and the main factor controlling draft is the effective pressure exerted upward from the ripper teeth. If the standard is straight, the main factor controlling draft is the direct horizontal pressure of the soil on the standard.

A final variable to be considered in relation to the depth of operation is the number of standards on the ripper. Reductions in draft can be accomplished by reducing the number of standards and by

increasing the space between them. The Kellough Brothers' five-shank ripper with 55 cm spacing between standards may be converted to a three-shank ripper with 110 cm spacings between standards (E. Kneeland 1983, personal communication). This is accomplished by removing the second and fourth standards. The accompanying reduction in draft allows for the use of smaller tractors or greater depth penetration.

Having assessed some of the practical limitations to achievement of the desired depth of ripping, a closer examination of what the desired depth should be is in order. Ripping experiments performed on compacted, silty clay, sugar cane fields in Hawaii revealed that little benefit is gained from increasing the ripping depth below 40 to 45 cm (Trouse and Humbert 1958). Increasing the depth of ripping beyond this point caused relatively little increase in the mean thickness of soil loosened. Furthermore, this procedure resulted in substantially increased power requirements.

Increasing the depth of ripping would appear to lengthen the narrow channel of plastic shear flow without expanding the zone of shear plane development. One study indicated that ripping to a depth of 43 cm on a soil in Oregon with an impermeable layer extending from 30 to 45 cm failed to increase the hydraulic conductivity below the 25 cm depth (Allmaras et al. 1977). The authors of this study concluded that the "small increase of internal drainage for ripping deeper than 25 cm does not justify the associated energy expenditure".

Other factors which are considered important to soil loosening by ripping are the number and direction of operations conducted. The majority of experiments carried out thus far have dealt with a single operation. However, because of the reduced costs associated with ripping, as compared to deep plowing, many farmers are looking at multiple ripping as an option. A comparison of the costs of operating Kellough built deep plows versus Kellough built deep rippers showed that plows were about 35% more expensive (Drever and Wiens 1980). Multiple ripping would therefore be cheaper, assuming that much less draft was required on the second and third passes.

Crossing patterns studied in the literature include: a 45 degree single cross, a 90 degree single cross, a 90 degree double cross, and 45 - 90 degree double cross (Trouse and Humbert 1958; Allmaras et al. 1977). Results indicate that the 45 degree single cross is slightly more effective at soil loosening than is the 90 degree single cross, and that double crossing operations are slightly better than single cross operations (Trouse and Humbert 1958). Intersubsoiling, or ripping in the same direction between previously tilled shank tracks was shown to be extremely difficult because the ripper shanks would eventually migrate back into the pre-existing set of grooves (Trouse and Humbert 1958).

2.3 EFFECT OF TILLAGE ON REDISTRIBUTION OF SALTS

The impact of deep plowing on soil chemical properties has been well documented. Numerous studies have shown increased pH and electrical conductivity in surface horizons as a result of deep

plowing (Harker et al. 1977; Lavado and Cairns 1981; Ballantyne 1983). A lowering of exchangeable and soluble sodium levels in the profile was also noted (Cairns 1962; Cairns and Bowser 1967; Cairns 1969; Karkanis and Cairns 1981; Ballantyne 1983), although some authors observed an increase in soluble and exchangeable sodium in surface horizons (Harker et al. 1977; Lavado and Cairns 1981). In the situation where deep plowing increased soluble sodium levels in surface horizons, the calcium to sodium ratio was widened because of accompanying increases in calcium levels (Harker et al. 1977). Conversely, when deep plowing decreased soluble sodium levels throughout the profile, soluble calcium and magnesium levels were also reduced, but to a much lower extent, resulting once again in increased calcium to sodium ratios (Cairns and Bowser 1967). Increasing or decreasing total salt levels widened the calcium to sodium ratio and improved the pre-existing deleterious cation ratios.

Investigations into the influence of ripping on soil chemical properties are scant in the literature. Research done in Colorado involving sampling in the shank track and 20 cm to the side of the track showed evidence of lateral movement of salt away from the shank track at two of four sites (White et al. 1981). Extractable sodium and electrical conductivity values were lower in the shank zone as compared to 20 cm over. Less detailed sampling, done without regard for shank location in Alberta, revealed that ripping increased extractable sodium in the Ap horizon, increased the pH in the Bnt horizon, and decreased extractable calcium levels in the Bnt horizon (Lavado and Cairns 1981). None of these changes could be viewed as positive for long-term amelioration purposes.

3. MATERIALS AND METHODS

3.1 SITE DESCRIPTION

3.1.1 Location of Study

Experiments were conducted in two adjacent fields located approximately 11 km northwest of Halkirk, Alberta (Figure 3). The legal locations of the two quarter sections were SW 3-40-16-W4 and NW 34-39-16-W4. For the purpose of simplification, the field located in the southwest corner of section 3 will be referred to as the "North Field", and the field located in the northwest corner of section 34 will be referred to as the "South Field".

3.1.2 Soils

A soil survey report published in 1951 at a scale of 1:190,000 had the two quarter sections in the study area mapped in an area covered by 50% Torlea loam and 50% Gadsby loam (Bowser and Peters 1951). Torlea loam is described as a Dark Brown Solonetz ⟶ Solodized Solonetz developed on relatively undisturbed residual material of the lower Lake Edmonton formation. Gadsby loam is described as a Thin Black Solodized Solonetz developed on glacial lacustrine material with a medium to high salt content.

A more recent soil survey, initiated in 1981, done at a more detailed scale (1:50,000) has the area under investigation in this study mapped as a Halkirk-Torlea map unit (Wells and Nikiforuk 1984).

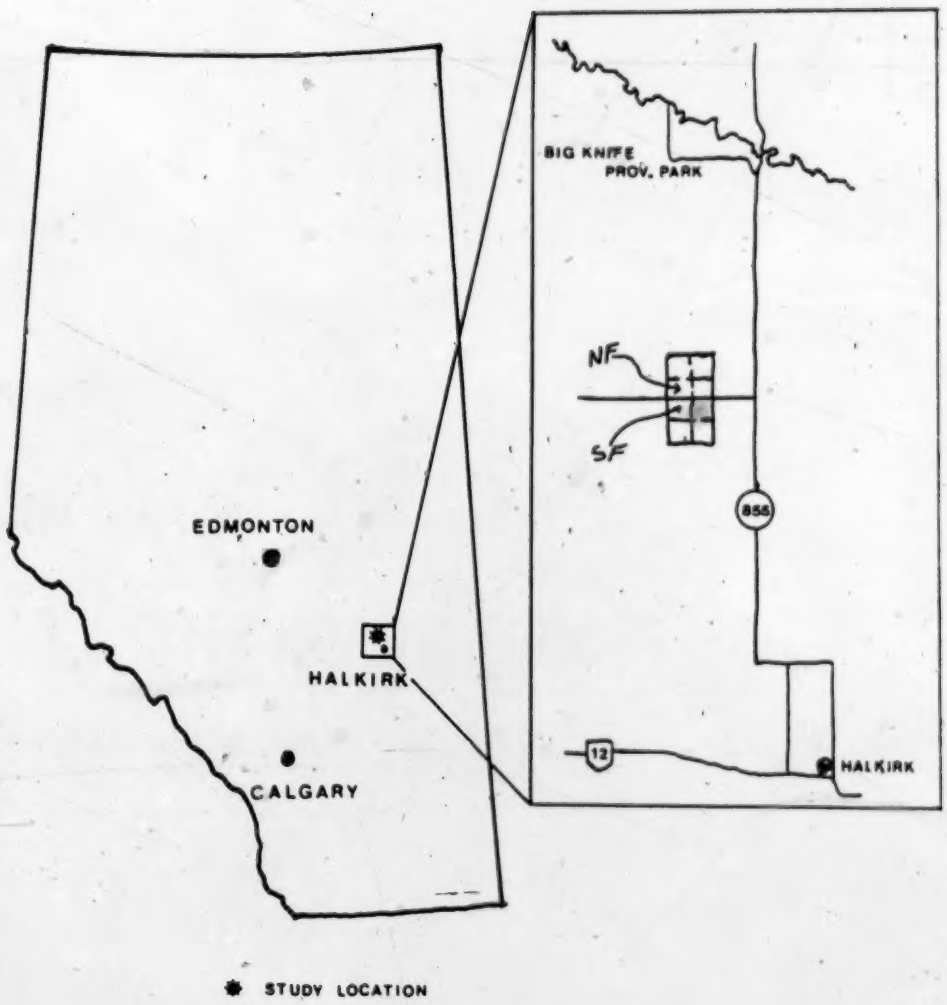


Figure 3. Field location of deep ripping plots.

Both Halkirk and Torlea are Dark Brown Solodized Solonetz soils, with Halkirk developing on till and Torlea developing on residual material. The Halkirk-Torlea map unit is described as occurring on a thin, occasionally discontinuous, till veneer overlying residual or modified residual shale (Wells and Nikiforuk 1984). Another parent material inclusion occurring within the immediate study area is a fluvial veneer over residual giving rise to pockets of Sullivan Lake soil series (personal communication, R. Wells, Research Officer, Alberta Research Council). The pockets of sandy material were unpredictable and could not be delineated at a scale of 1:50,000.

An even more detailed soil survey of the Alberta Agriculture plots in the North Field was carried out in conjunction with a project to assess the feasibility of using color infrared photography for mapping Solonetzic soils in east-central Alberta (Wells and Hermans 1985). This survey, done at a scale of 1:31,680 on color infrared photographs, shows the study area in the North Field to, once again, be on a Halkirk-Torlea map unit.

3.1.3 Surfical Geology

The study area lies within the Torlea Flats Lowland physiographic division. The region is characterized by landscapes with low relief and rolling to undulating surface expressions. The majority of the land is underlain by soft, Upper Cretaceous bedrock which exerts great control over surface features (Stalker 1960). Surficial deposits occurring on the two quarter sections at the study site are described as Upper Cretaceous bedrock covered by thin slump, alluvium

or drift in localized areas (Stalker 1960). There has been little Pleistocene or recent deposition in the area, which is a common feature among areas adjoining Paintearth Creek. The two arms of Paintearth Creek run north and south of the study site, approximately 1 km in each direction, and join each other 3 km east of the study site. Paintearth Creek is described as a former meltwater channel (Stalker 1960) and is the most striking surficial feature in the immediate vicinity of the study area.

3.1.4 Hydrogeology

The study area is located within an area defined as having a "sluggish groundwater flow system" (Le Breton 1971). Low local relief, limited number of springs and the temporary nature of creeks all indicate scarce availability of groundwater resources. Average expected well yields are less than one imperial gallon per minute in the vicinity of the study area (Le Breton 1971).

Results of groundwater chemistry investigations in the study area show that chloride is the dominant anion from sources found below 70 to 80 m and carbonate-bicarbonate is the dominant anion from sources above 70 m. Sodium and potassium are the dominant cations found in groundwater from either shallow or deeper sources (Le Breton 1971).

Concerning groundwater flow direction, little can be discerned on a local or intermediate scale because of the lack of relief and because no site specific investigation was carried out. On a regional scale the study area lies within an area of upward

groundwater movement. Regional recharge areas are found in highland regions near Red Deer, some 100 km west of the study area.

3.2 PLAN OF TILLAGE PLOTS

As part of a program to assess the merits of deep plowing, tillage experiments were first initiated by Alberta Agriculture in the North Field. In the fall of 1976, two 45 m wide strips were plowed on the western edge of the field using a conventional moldboard plow and a three-bottomed topsoil saving plow (Figure 4). As a follow-up to this work, another test strip was cultivated in the fall of 1978 (Figure 4), using a Kellough Brothers series 5000 Deep Ripper. This strip was separated from the deep plowing plots by a check strip, which was subject to shallow conventional tillage operations only.

In the South Field, there were no formal tillage plots designed by Alberta Agriculture. However, the entire field was ripped by the cooperating farmer, Ernie Kneeland, in the fall of 1979.

3.3 DEEP RIPPING OPERATIONS

The Kellough 5000 deep ripper consists of five slightly curved standards, each with its own ripper tooth (Plate 1). The standards are normally spaced 56 cm apart. Depth of operation, as perceived from visual observations of trenches excavated perpendicular to the direction of tillage, varied between 36 and 42 cm. In order to maintain this depth of operation, a tractor with considerable horsepower (200-225 H.P.) was used.

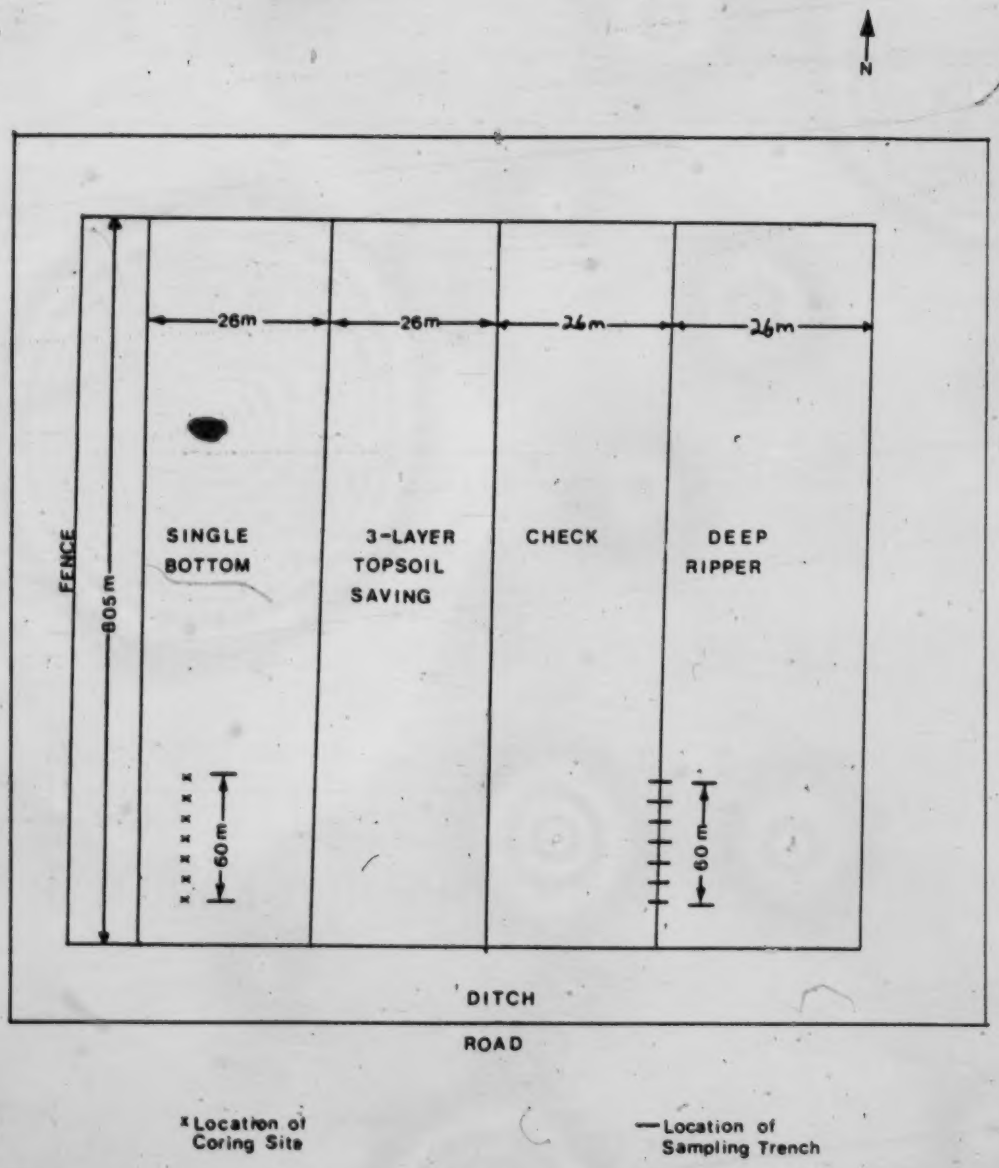


Figure 4. Outline of Alberta Agriculture Plots located in North Field SW 3-40-16-W4.

Plate 1. Kellough 5000 Deep Ripper.

Ripping operations in the South Field was done by removing two standards located adjacent to the two outside standards leaving only three standards, spaced 112 cm apart. Depth of operations, calculated in the same fashion as for the North Field, varied between 30 and 38 cm.

3.4 SAMPLING TECHNIQUES

Soils samples were collected for chemical analyses in the fall of 1982 and in the spring of 1983. The sampling procedure used in the North Field involved the following sequential steps. An initial sampling point was located 33 m in from the south fence line, along the boundary between the check strip and the deep ripping strip. A trench, approximately 3 to 4 m long, 1 m wide and 1 m deep, was then excavated perpendicular to the direction of ripping along the boundary. A Bobcat tractor, equipped with a portable backhoe, was used to dig the trenches (Plate 2). Once the trench was opened, the check strip was sampled on a horizon basis to the approximate depth of ripping 36 to 42 cm. Two sets of samples were then taken from each horizon. A large sample (4 kg) was intended for general chemical analysis and a small sample (1 kg) was used for analysis of nitrogen status only.

After having sampled the check strip, as near to the boundary with the ripping strip as possible, the next step was to locate the first adjacent disturbed zone caused by the ripper shank. This was accomplished through visual observation and by probing with a screwdriver (Plate 3). In cases where the disturbed zone was not

Plate 2. Bobcat tractor used to excavate sampling pits.

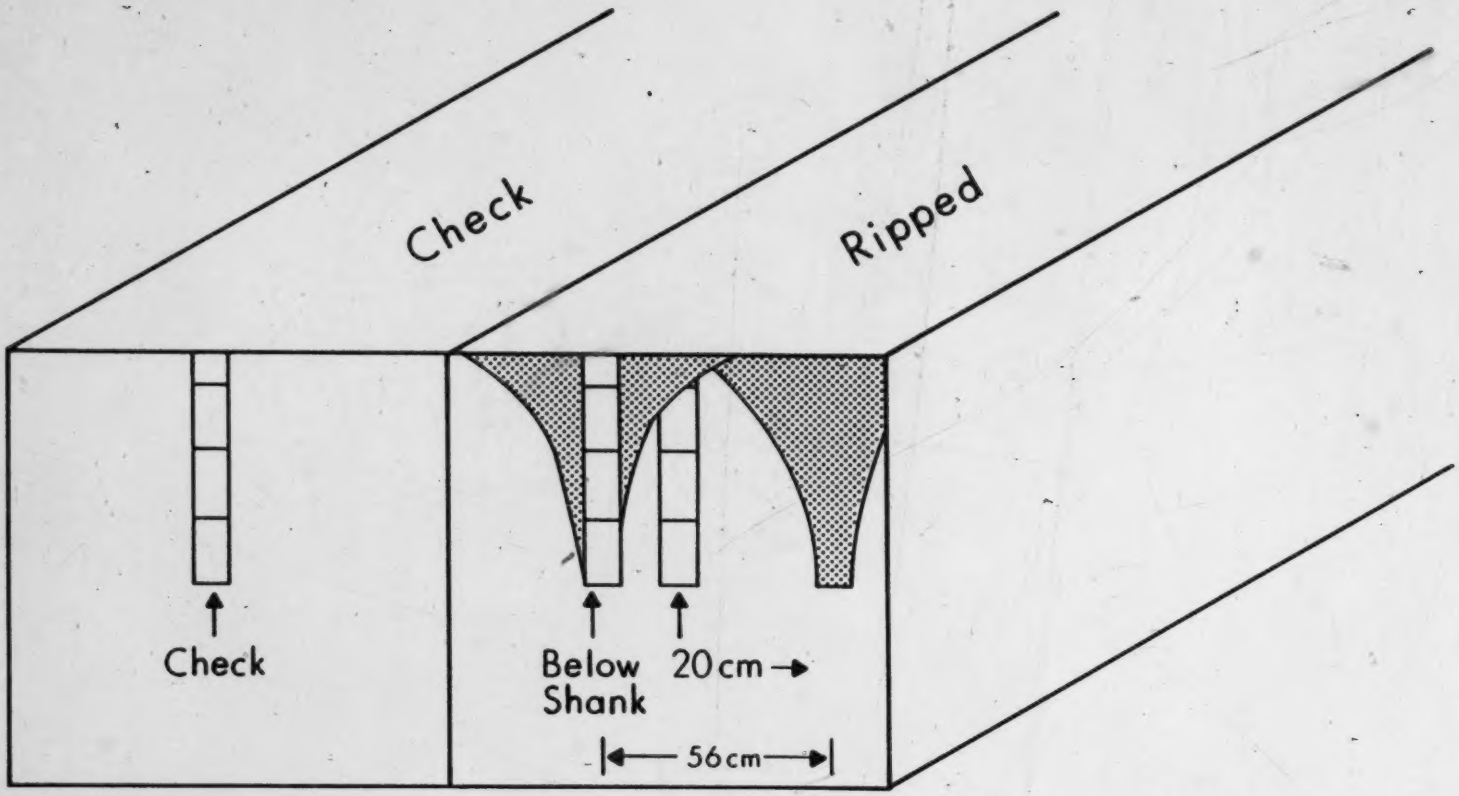
Plate 3. Disturbed zone where the ripper shank had passed through the soil. Disturbed zone outlined by orange flagging extending to a depth of 40 cm.

immediately obvious, it was most often located by probing for a moist slot of plastic consistency between the depths of 30 and 40 cm. This was thought to represent the zone of plastic shear occurring at the bottom of the ripper standard.

Having located the first zone of disturbance adjacent to the check strip, the authenticity of this finding was verified by trying to locate a similar zone of disturbance centered 56 cm further into the ripped strip (ripper shanks were spaced 56 cm apart). Once confidence in the location of the first disturbed zone adjacent to the check strip was established, samples were taken at equivalent depths to the horizons identified in the check strip. Samples were taken down the center of the disturbed zone, in the narrow area (10 cm wide) where the ripper shank had passed through the soil (Figure 5). Again, two sets of samples from each depth were taken. Samples from this area were referred to as "Below Shank".

The final set of samples were taken from the trench in a narrow zone (10 cm wide) located 20 cm to one side of the zone designated Below Shank (Figure 5). Both large and small samples, as described previously, were taken and labelled "20 cm $\longrightarrow$".

Once samples had been taken from the Check, Below Shank, and 20 cm $\longrightarrow$ areas, a white stake was positioned at the boundary between the check and ripped areas, and the trench was backfilled. The sampling location for the next trench was then located by advancing 10 m northward up the field. In order to stay as close as possible to the boundary between the two strips, the stake located at the backfilled trench and the stake located on the fence line were used



SHADED AREA REPRESENTS DISTURBDED ZONE.

DIAGRAM NOT DRAWN TO SCALE.

Figure 5. Sampling locations for soil chemistry within the check strip, below the shank and 20 cm to one side of the shank (North Field).

as markers. This step was taken with the realization that the boundary was not absolutely straight, due to wandering of the implement during tillage. The entire process of sampling was then repeated six times to give a total of seven sampling trenches in the North Field (Figure 4). The first five trenches were completed in the fall (October) of 1982 but because of inclement weather the last two were dug and sampled in the spring (April) of 1983.

In addition to the above operations, samples were taken for comparative purposes from the single bottom deep plowed strip located in the North Field. Once again, an initial sampling point was established 33 m into the field and slightly off-center. At this site, core samples were taken at equivalent depths to the horizons identified in the check strip as discussed earlier. A 10 cm diameter hand auger was used. This process was then repeated six additional times, at 10 m intervals, to give seven coring locations (Figure 4). Duplicate samples were not taken at each depth because analysis for nitrogen status was not done for this treatment in the North Field.

The sampling technique used in the South Field was similar to that employed in the North Field, except that no formal check strip was sampled. An initial sampling location was established 33 m into the field and a trench of the same dimensions as discussed for the North Field was excavated perpendicular to the direction of ripping.

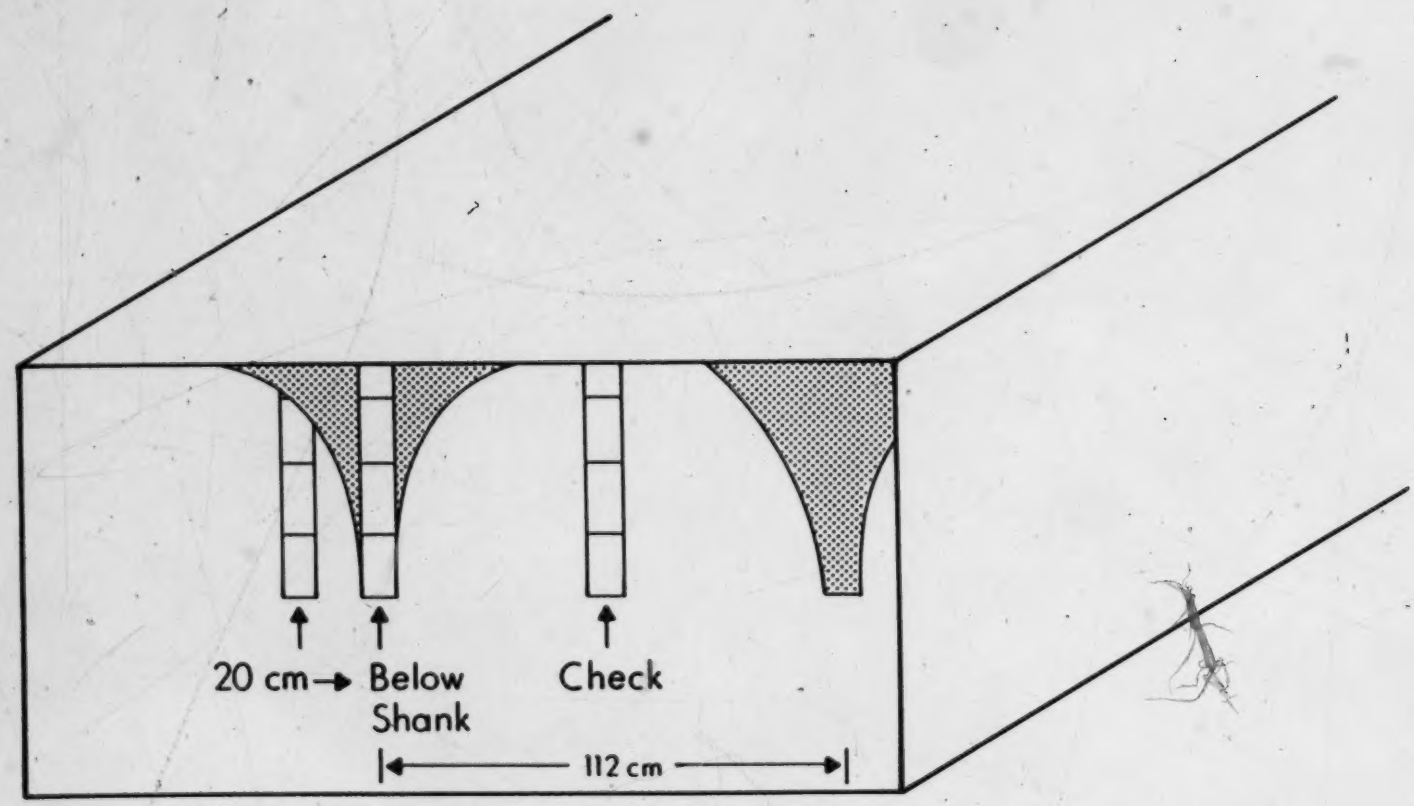
Once the trench had been excavated, the first step was to locate the disturbed shank zones adjacent to each other. Finding the disturbed areas was easier in this field than in the North Field because they were more widely spaced and also because they were one

year younger. The centers of these disturbed areas were 112 cm apart (shank spacing 112 cm). The check area was then taken to be the undisturbed zone occurring at the midpoint between the two shank zones. Samples representing this check area were then taken in a narrow band (10 cm wide) on a horizon basis (Figure 6).

Samples were taken next from the Below Shank and 20 cm → areas at the same depths as in the check area. As was the case for the ripping samples in the North Field, at each depth large samples were taken for general chemical analysis and small samples were taken for nitrogen analysis only. Seven trenches, spaced 10 m apart, were excavated in total. Once again, the first five trenches were made in the fall (October) of 1982 and the final two were completed in the spring (April) of 1983.

3.5 SAMPLE PREPARATION

The small samples taken at each depth from the ripping trenches were air-dried immediately at 20°C for 48 h. Special attention was paid to these samples because they were taken for nitrogen analysis. Samples taken for nitrogen status (nitrate + ammonium) should not be oven-dried and should not be allowed to remain moist for any extended period of time (L. Kryzanowski 1983, pers. comm.). Allowing the samples to remain moist in a warm environment facilitates microbial transformations, and oven-drying the samples causes problems associated with elevated ammonium levels (L. Kryzanowski 1983, pers. comm.). After the nitrogen samples were dried, they were ground, using a swing-mill grinder, until they passed a 2 mm sieve. They were then stored for analysis.



SHADED AREA REPRESENTS DISTURBDED ZONE.

DIAGRAM NOT DRAWN TO SCALE.

Figure 6. Sampling locations within the check strip, below the shank and 20 cm to one side of the shank (South Field).

The larger samples, intended for general chemical analysis, were also air-dried, but not as rapidly. These samples were allowed to remain in the bag until they were transported to the Ellerslie experimental farm. They were then allowed to air-dry over an extended period (2 weeks) and were then ground to pass a 2 mm sieve on the rollerball mill.

In an attempt to reduce the chances of salt contamination from grinding, only samples from equivalent depths were ground together. For example, all the surface horizons were ground first, then the second layer samples, and so on. Although the grinding machine was cleaned well after each sample was ground, it was felt that it would be wise to grind the low salt samples first and then the high salt samples. Following the grinding procedure, the samples were stored in plastic containers for analysis.

3.6 SAMPLE ANALYSES

3.6.1 Chemical Analyses

Sodium status of soil samples can be assessed by either exchangeable sodium percentage (ESP) or sodium adsorption ratio (SAR). Recent literature has placed a greater emphasis on the use of SAR because of the tedious nature and experimental errors associated with determining ESP values (Bohn et al. 1979; Bresler et al. 1982). ESP determinations require an accurate estimate of exchangeable sodium, corrected for soluble sodium (ascertained from a saturation extract) and an accurate estimate of total cation exchange capacity.

Each of these steps is time consuming and error prone. SAR determinations, on the other hand, require only a saturation extract. Therefore, for the sake of reducing experimental error and time requirements, SAR was selected over ESP as the criterion for evaluating soil sodium status.

Soluble cations (Ca^{++}, Mg^{++}, Na^{+} and K^{+}) and anions ($SO_4^{=}$, HCO_3^{-} and $CO_3^{=}$) were determined on solutions extracted from saturated soil pastes. Saturated pastes were prepared according to procedures outlined in Methods of Soil Analyses (Page et al. 1982). Saturated pastes were allowed to stand 20 to 24 hours before extraction was started. In order to facilitate greater extraction volumes, each paste was transferred to two Buchner suction funnels.

Soluble Ca^{++}, Mg^{++}, Na^{+} and K^{+} were determined by atomic absorption spectrophotometry (Page et al. 1982). Soluble Na^{+} was also determined using flame emission techniques on the same instrument because values were usually slightly higher and more reproducible than those determined by atomic absorption.

Initial determinations of soluble sulfate involved using both a turbidimetric method (American Public Health Association 1971) and a colorimetric method (Lazarus et al. 1966). The colorimetric method was eventually chosen because the results were more reproducible and use of the autoanalyzer saved a lot of time. Carbonate and bicarbonate were determined by pH titration using an autotitrator.

Electrical conductivity of saturated paste extracts was determined on a YSI Model 31 Conductivity Bridge following the manufacturer's instructions.

Hydrogen ion activity was measured on soil-water solutions having a ratio of 1:2.5 (McKeague 1978).

Nitrogen samples were analyzed for extractable nitrate and ammonium at the Alberta Soil and Feed Testing Laboratory. Extraction was done by using 2N KCl. Analyses for nitrate and ammonium were done on the autoanalyzer using industrial methods (Technicon No. 487-77A and Technicon No. 98-70W, respectively).

3.6.2 Physical Analyses

Particle size analyses was done on all ripping samples taken from both fields using the hydrometer method (McKeague, 1978). Readings, using a standard hydrometer, were taken at times of 1 minute and 12 hours to separate sand and clay fractions, respectively.

Available moisture was ascertained on selected ripping samples from both the North and South Fields. Moisture retention at -33 kPa and -1,500 kPa was determined using pressure plate apparatus (Richards 1965). The sample, out of seven replicates, having the clay content nearest to the average clay content determined for a given treatment at a given depth was selected for analysis. The same process was used in both the North and South Fields.

3.7 MONITORING OF SOIL MOISTURE

Soil moisture content was determined in 5 cm depth intervals from 0 to 40 cm at seven locations in the South Field during the summer of 1983 (May to August). The first measurements were taken on

May 26, 1983, and subsequent measurements were taken at either weekly or biweekly intervals thereafter until August 22, 1983. Sampling locations were established at the midpoint between former chemistry sampling pits, which had been excavated and marked the previous fall and spring (Figure 7).

As was the case in sampling for chemical analysis, moisture samples were taken from the undisturbed check area between shank disturbed zones, from the center of the shank disturbed zone, and 20 cm to one side of the shank disturbed zone (Figure 7). Sampling was done with a narrow diameter (1.5 cm) Oakfield sampler. Centers of the shank disturbed zone were located on the basis of differential stubble density. Observations made the previous fall when the trenches were open showed that the wheat stubble was considerably denser (thicker stalks and more stalks per m^2) in the central areas of the shank disturbed zone compared to the undisturbed areas. Samples were removed at 5 cm intervals and immediately placed in sealed plastic bags. The samples were then stored in a styrofoam cooler for transport to the laboratory. The moist samples were weighed on a Mettler Electronic Balance and placed in a drying oven (105°C) for 48 h. In total, 168 samples were weighed to two decimal places after each sampling. The oven-dry samples were allowed to cool in a desiccator and were then re-weighed on the same balance. Gravimetric moisture contents were calculated.

Gravimetric sampling does not allow the same spot to be sampled over time, so the sampling location had to be moved each week. After each hole was cored, the hole was backfilled as best as possible, and

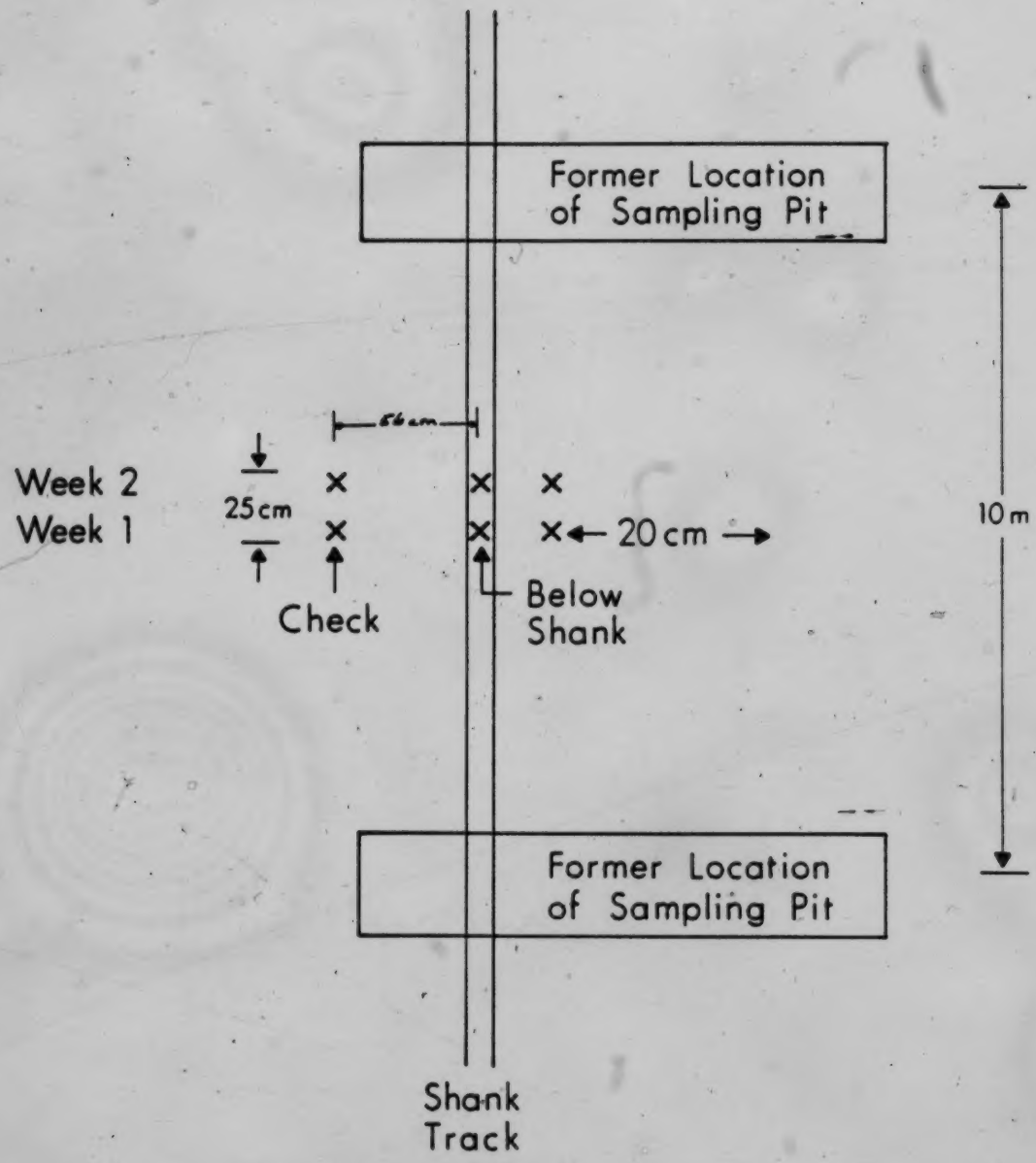


Diagram not drawn to scale.

Figure 7. Diagram outlining sampling procedure for moisture samples taken throughout the summer of 1983.

marked with a very small stake. When it was time to sample at that location the next week, cores were taken 25 cm in a line from the previous location (Figure 7).

Weekly precipitation levels were monitored using a standard Alberta Forest Service rain guage. A small film of kerosene was added each week to prevent evaporation.

4. RESULTS AND DISCUSSION

4.1 RESULTS (CHEMISTRY)

The principal investigation into soil chemistry centres on the analysis of saturation paste extracts. The electrolytic strength and composition of each solution were determined by measuring electrical conductivity and concentrations of the major cations and anions. Complete data obtained from this investigation are presented in Appendix 1.

In the initial assessment of these data, cation-anion balances of each solution were checked to ensure that the principle of electro-neutrality was upheld. A computation was used to determine the differences between the sum of cations and the sum of anions, divided by the sum total of cations and anions.

$$\frac{\text{Difference between cations and anions}}{\text{cations + anions}} \times 100$$

When the value of this ratio was 15% or less, approximate electro-neutrality was assumed, thus indicating the absence of any erroneous values. In cases where the ratio exceeded 15%, laboratory measurements and calculations were repeated to check for errors. Errors were occasionally found in the sodium and sulfate measurements.

4.1.1 Sodium Adsorption Ratio (SAR)

Having checked for errors in the laboratory analyses, steps were taken to ascertain whether deep ripping had altered the suite of

cations present in the soil solution. To this end, a comparison was made of the SAR values of a number of soil samples. These samples were taken from areas directly beneath the shank, 20 cm to the side of the shank (20 cm $\longrightarrow$) and in the undisturbed check area. The SAR constitutes a value designed to reflect the extent to which sodium dominates in a given soil solution.

$$SAR = \frac{Na+}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}} \quad *$$

* Ion concentrations expressed in meq/l.

Potassium is not included in the ratio because it occurs in such low concentrations with respect to the other cations that its presence in the equation would be negligible. The SAR values are depicted in table and graph form for various treatments and horizons (Tables 4 and 7 and Figures 8 and 9).

SAR values increased with depth for all three treatments in the North Field (below shank, 20 cm $\longrightarrow$ and check) and all three followed the same trend (Figure 8). Statistical analyses based on a factorial experimental design, with the three treatments, four depths and seven replicates, showed no significant differences between the treatments within each depth or treatment-depth interactions (Table 1).

Also plotted on Figure 8 are the mean SAR values of seven corresponding sampling sites from an adjacent deep plowed plot.

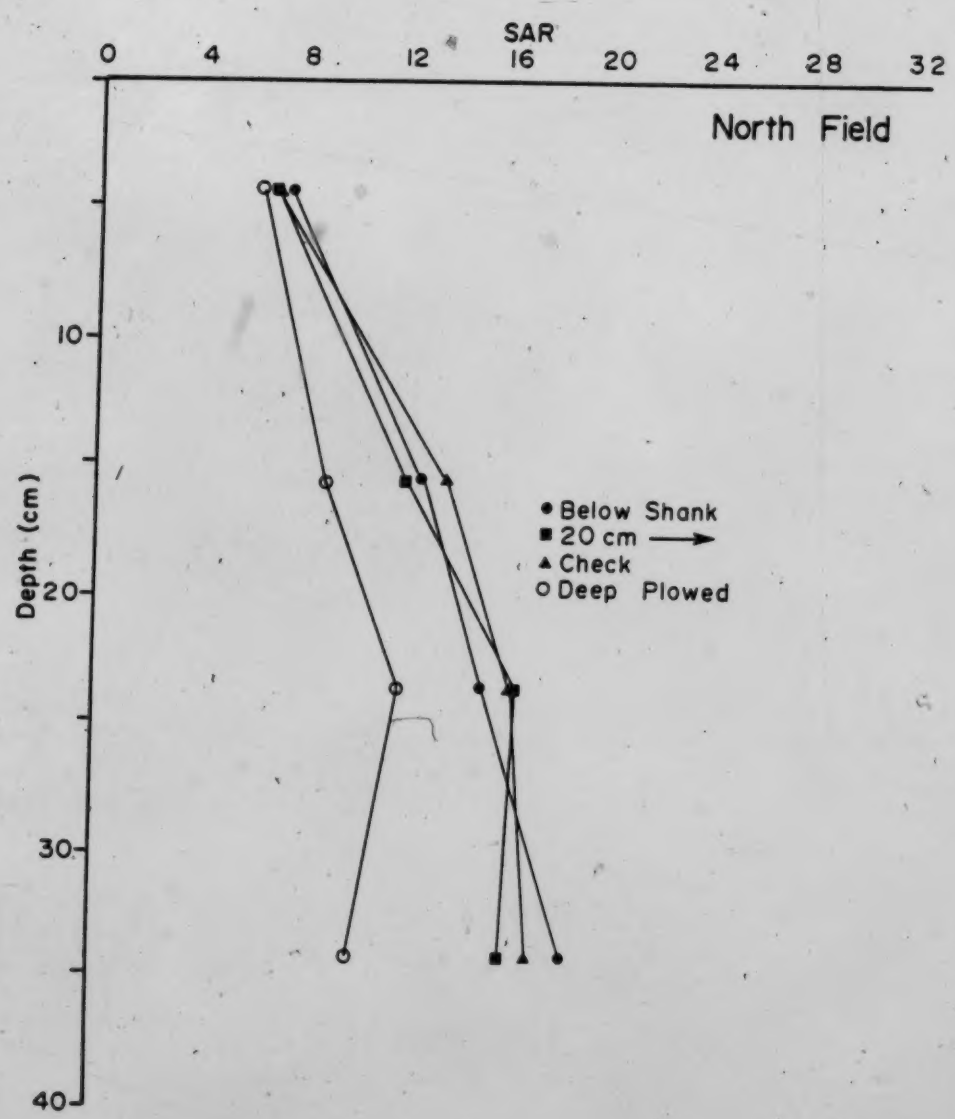


Figure 8. Sodium adsorption ratio (SAR) vs depth for ripping and deep plowing treatments (North Field).

Table 1. Analysis of variance for SAR, EC and pH data from ripping treatments (North Field).

Source of Variation	df	SS	MS	f-ratio	Sig[n1]
SAR					
Replicates	6	1,535.4	255.9	12.0	**
Depth	3	1,277.8	425.9	20.0	**
Treatment	2	7.2	3.6	0.16	NS
Depth x Treatment	6	27.0	4.5	0.21	NS
Error	65	1,381.2	21.2		
EC					
Replicates	6	58.6	9.8	6.1	**
Depth	3	78.1	26.0	16.2	**
Treatment	2	8.7	4.3	2.7	NS
Depth x Treatment	6	6.6	1.1	0.68	NS
Error	65	104.3	1.6		
pH					
Replicates	6	17.8	3.0	7.9	**
Depth	3	50.9	17.0	45.3	**
Treatment	2	1.0	0.50	1.34	NS
Depth x Treatment	6	2.4	0.40	1.04	NS
Error	65	24.3	0.37		

NS = Not significant
* = Significant ($p \leq 0.05$).
** = Highly significant ($p \leq 0.01$).

Samples were taken at depths corresponding to horizons identified in adjacent pits excavated on the boundary between the check and ripped plots. A comparison of the deep plowed treatment to the check and shank associated treatments illustrates a reduction in the SAR as a consequence of deep plowing. An analysis of variance for SAR, based on four treatments (deep plowing, check, below shank and 20 cm $\longrightarrow$) and four depths, showed the treatment effect to be significant at the 0.05 level (Table 2). Multiple mean comparisons, using the least significant difference test, revealed a significance difference in SAR values between the deep plowed means and the other three (Table 3). Differences between the three treatment means associated with ripping were not significant (Table 3). The treatment-depth interaction was not significant (Table 2) in this instance, so multiple means comparisons were not performed.

Replication was not included as a primary effect in the analysis of variance for the comparison of deep plowing with ripping. This was because of the lack of proximity between the sampling locations. The three treatments associated with the ripping investigation were considered replicated because they were sampled very close to each other (within 1-2 m) whereas the deep plowed treatment was sampled 70 m away. If the basis for replication is said to be a similarity among soils, the probability that the ripping treatments (check, 20 cm $\longrightarrow$ and below shank) were acting on a similar soil at each replication was quite high. However, in the case of deep plowing, it is impossible to know whether the sample under scrutiny is actually a similar soil to that sampled at an adjacent trench on the check-

Table 2. Analysis of variance for SAR, EC and pH data from combined ripping and deep plowing treatments (North Field).

Source of Variation	df	SS	MS	f-ratio	Signl
SAR					
Depth	3	1,283.9	428.0	13.5	**
Treatment	3	333.3	111.1	3.50	*
Depth x Treatment	9	130.8	14.5	0.45	NS
Error	95	3,014.5	31.7		
EC					
Depth	3	139.4	46.5	23.2	**
Treatment	3	22.0	7.3	3.7	*
Depth x Treatment	9	16.8	1.9	0.93	NS
Error	95	190.1	2.0		
pH					
Depth	3	36.4	12.1	6.4	*
Treatment	3	8.4	2.8	1.5	NS
Depth x Treatment	9	17.4	1.9	4.0	**
Error	95	46.0	0.48		

NS = Not significant
* = Significant ($p \leq 0.05$).
** = Highly significant ($p \leq 0.01$).

Table 3. Multiple mean comparisons for treatment means for SAR using least significant difference test (North Field).

Treatment	Mean
Check	13.2 a[1]
Below Shank	13.4 a
20 cm ⟶	12.8 a
Deep Plowed	9.2 b

[1] Means not followed by same letter are statistically different according to LSD test ($p \leq 0.05$).

Table 4. Ranges, means and standard deviations for SAR values for soil samples from below shank, 20 cm ⟶, check and deep plowed areas (North Field).

Treatment	Range[1]	Mean	Standard Deviation
Ap Horizon (0-8.5 cm)			
Check	3.5-11.2	6.8	2.8
Below Shank	2.6-14.2	7.3	4.2
20 cm ⟶	2.0-14.8	6.8	4.4
Deep Plowed	2.3- 7.8	6.2	1.9
Bnt Horizon (8.5-22.5 cm)			
Check	3.8-25.2	13.6	7.0
Below Shank	2.2-19.2	12.6	6.4
20 cm ⟶	2.4-24.7	12.0	7.4
Deep Plowed	7.6-10.2	8.9	1.0
B-C Horizon (22.5-27.5 cm)			
Check	11.6-20.4	16.1	3.1
Below Shank	1.6-28.8	15.0	8.3
20 cm ⟶	2.1-31.9	16.3	8.8
Deep Plowed	6.9-15.6	11.8	2.6
Csk Horizon (27.5-40 cm)			
Check	13.1-24.4	16.9	3.6
Below Shank	1.9-30.7	18.3	8.7
20 cm ⟶	2.4-26.7	15.9	7.4
Deep Plowed	7.5-12.7	10.0	2.0

[1] Seven replicates.

ripping boundary. For this reason, the seven sites were considered repeats, and replicates were not isolated as a source of variation independent from the error term.

A different trend exists in the SAR-depth relationships in the South Field compared to that in the North Field (Figure 9). In the former, SAR values were higher for samples below the shank and 20 cm ⟶ areas than samples from the check. The analysis of variance for the ripping treatments revealed that treatment effects were significant at the 0.05 level (Table 5). Treatment-depth interactions, however, were not significant. Multiple mean comparisons of the treatment means, using the least significant difference test, showed the below shank treatment to differ from the check treatment (Table 6).

A partial explanation for the treatment effect being significant in the South Field and not in the North Field is recognition of differences in the shank spacing and in sampling techniques employed in the two fields. Identification of shank track zones was easier in the South Field (Table 5) than in the North (Table 1) because of the greater distance between adjacent shanks in the former. Locating shank tracks in the North Field was more difficult because, even though the trenches were located across the boundary between the undisturbed check area and the ripped area, the nearness of adjacent shanks (56 cm) resulted in a great overlap between disturbed zones. It was only at depth, near the bottom of penetration of the ripper shank, that patterns could be discerned, either visually or by probing for a slit containing moister, more plastic subsoil than the surrounding soil.

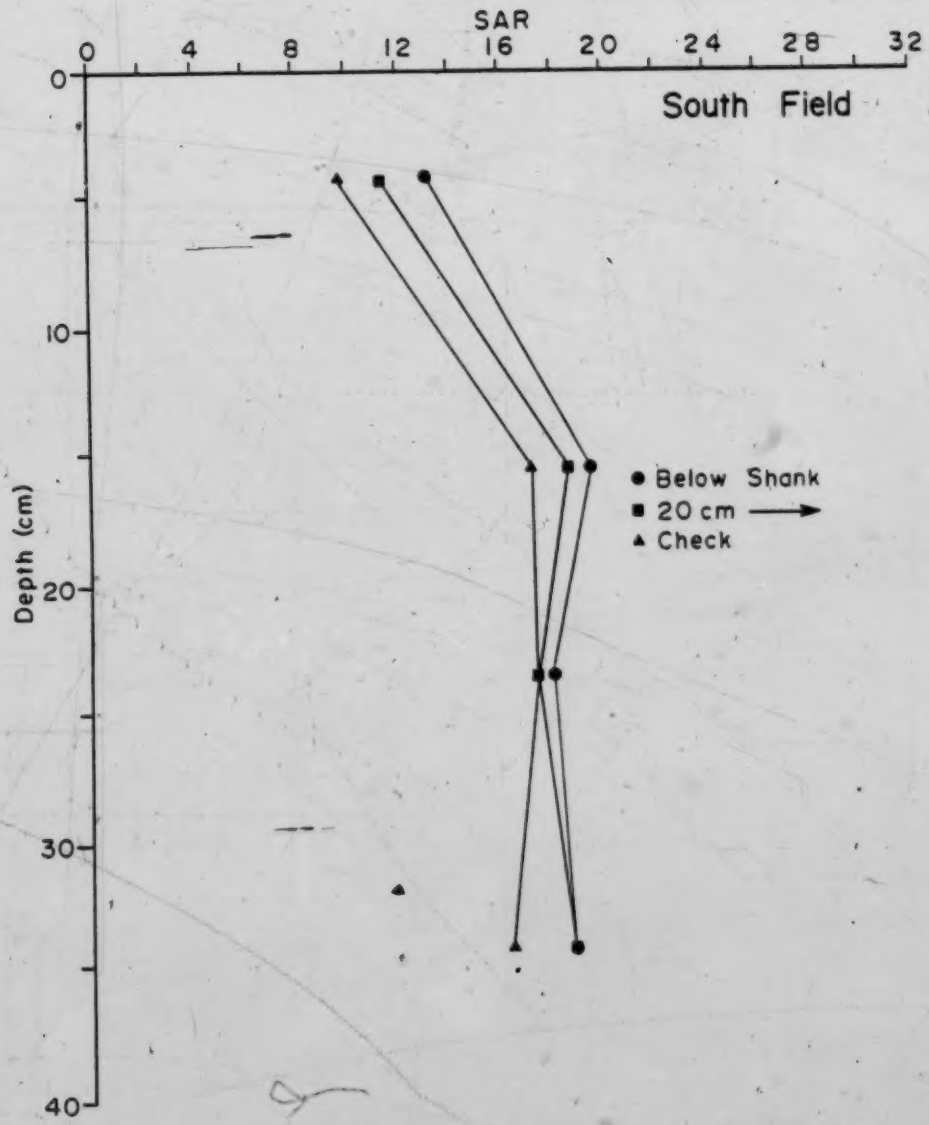


Figure 9. Sodium adsorption ratio (SAR) vs depth for ripping treatments (South Field).

Table 5. Analysis of variance for SAR, EC and pH data from ripping treatments (South Field).

Source of Variation	df	SS	MS	f-ratio	Signl
SAR					
Replicates	6	401.7	66.9	6.4	**
Depth	3	664.8	221.6	21.2	**
Treatment	2	62.6	31.3	3.0	*
Depth x Treatment	6	21.0	3.5	0.33	NS
Error	62	646.6	10.4		
EC					
Replicates	6	19.3	3.2	1.18	NS
Depth	3	83.7	27.9	10.3	**
Treatment	2	3.8	1.9	0.7	NS
Depth x Treatment	6	16.0	2.7	3.9	**
Error	62	42.4	0.68		
pH					
Replicates	6	6.4	1.1	1.57	NS
Depth	3	68.4	22.8	32.6	**
Treatment	2	5.7	28	4.0	NS
Depth x Treatment	6	4.2	0.70	2.7	*
Error	62	16.2	0.26		

NS = Not significant
* = Significant ($p \leq 0.05$).
** = Highly significant ($p \leq 0.01$).

Table 6. Multiple mean comparisons for treatment means for SAR data using least significant difference test (South Field).

Treatment	Mean
Check	15.2 a[1]
Below Shank	17.2 b
20 cm ⟶	16.6 a

[1] Means not followed by same letter are statistically different according to LSD test ($p \leq 0.05$).

Table 7. Means, ranges and standard deviations for SAR values for soil samples from check, below shank, and 20 cm ⟶ areas (South Field).

Treatment	Range[1]	Mean	Standard Deviation
Ap Horizon (0-8.5 cm)			
Check	6.7-12.2	9.7	2.2
Below Shank	8.2-17.4	13.1	3.3
20 cm ⟶	5.0-14.5	11.4	3.4
Bnt Horizon (8.5-22.5 cm)			
Check	9.4-23.8	17.2	6.8
Below Shank	16.9-25.6	19.5	3.0
20 cm ⟶	12.6-30.2	18.6	6.4
B-C Horizon (22.5-27.5 cm)			
Check	10.8-23.4	17.3	4.1
Below Shank	13.2-23.4	17.9	3.4
20 cm ⟶	13.9-22.3	17.4	2.8
Csk Horizon (27.5-40 cm)			
Check	13.6-20.7	16.3	2.8
Below Shank	15.6-23.7	18.7	3.1
20 cm ⟶	16.6-24.6	18.7	2.7

[1] Seven replicates.

Given the additional problems of locating shank tracks and overlap between disturbed zones, which were inherent in the process of sampling in the North Field, it appears inevitable that the data obtained from such samples would demonstrate increased variability. The chances of identifying a clear trend in the data are reduced as a result of the aforementioned problems of sampling.

Comparisons of ranges and standard deviations for SAR values on samples taken from below the shank and 20 cm ⟶ depths from both fields reveal increased variability in the North Field (Tables 4 and 7). The wider fluctuations about the mean could be attributed to sampling error or, quite possibly, to greater disruption and partial mixing caused by this narrower shank spacing. Interestingly, SAR values showed the least variation in the deep plowed field, where a drastic treatment that completely inverted and mixed the soil profile had been employed.

4.1.2 Electrical Conductivity (EC)

Electrical conductivities of saturation extracts for soil samples from both fields were made to determine their electrolytic strength. Once again, the mean values of seven replicates are plotted against the mean horizon depths for each field. The trends in the two fields were similar. Saturation extracts from samples taken 20 cm to one side of the shank track contained relatively higher salt contents than those of the check and below shank samples in the lowest two horizons (Figures 10 and 11). Statistical analysis based on a factorial design with seven replicates, four depths and

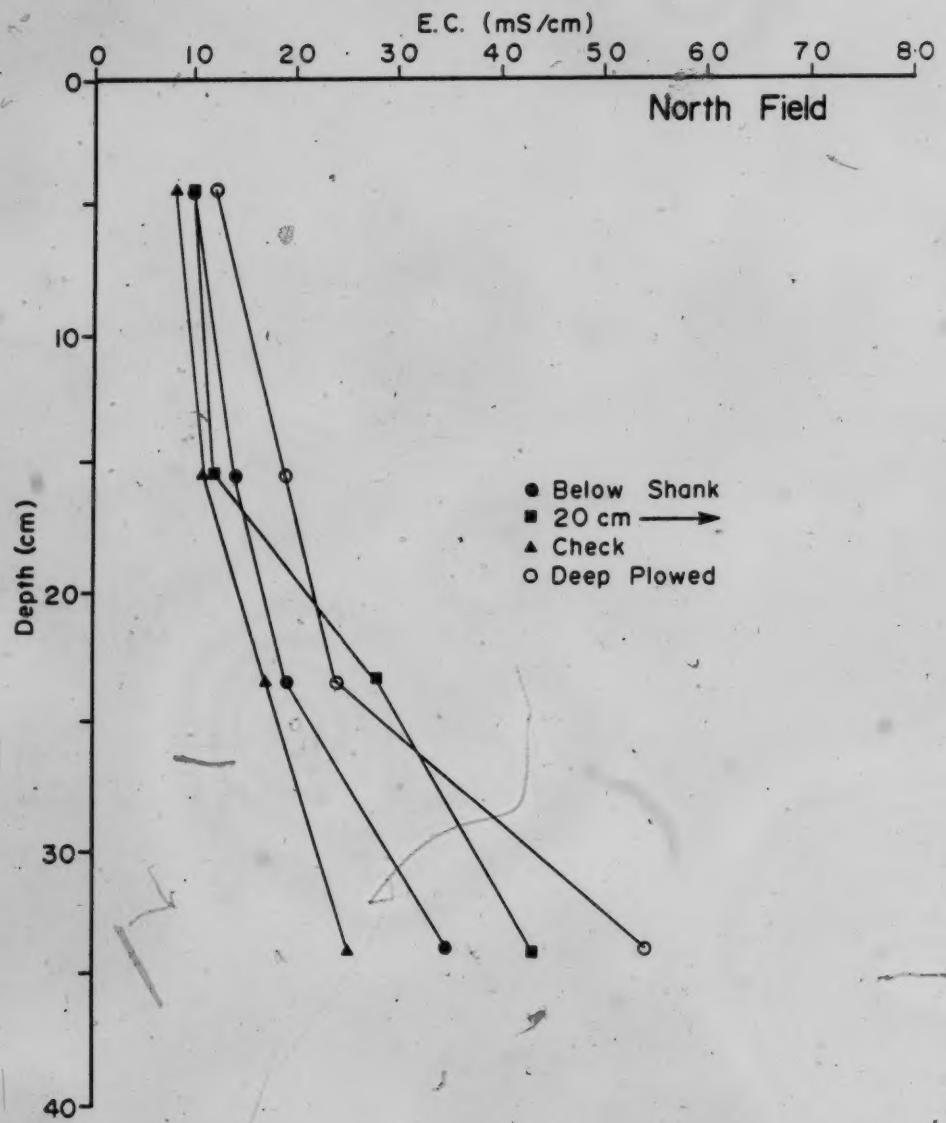


Figure 10. Electrical conductivity (EC) vs depth for ripping and deep plowing treatments (North Field).

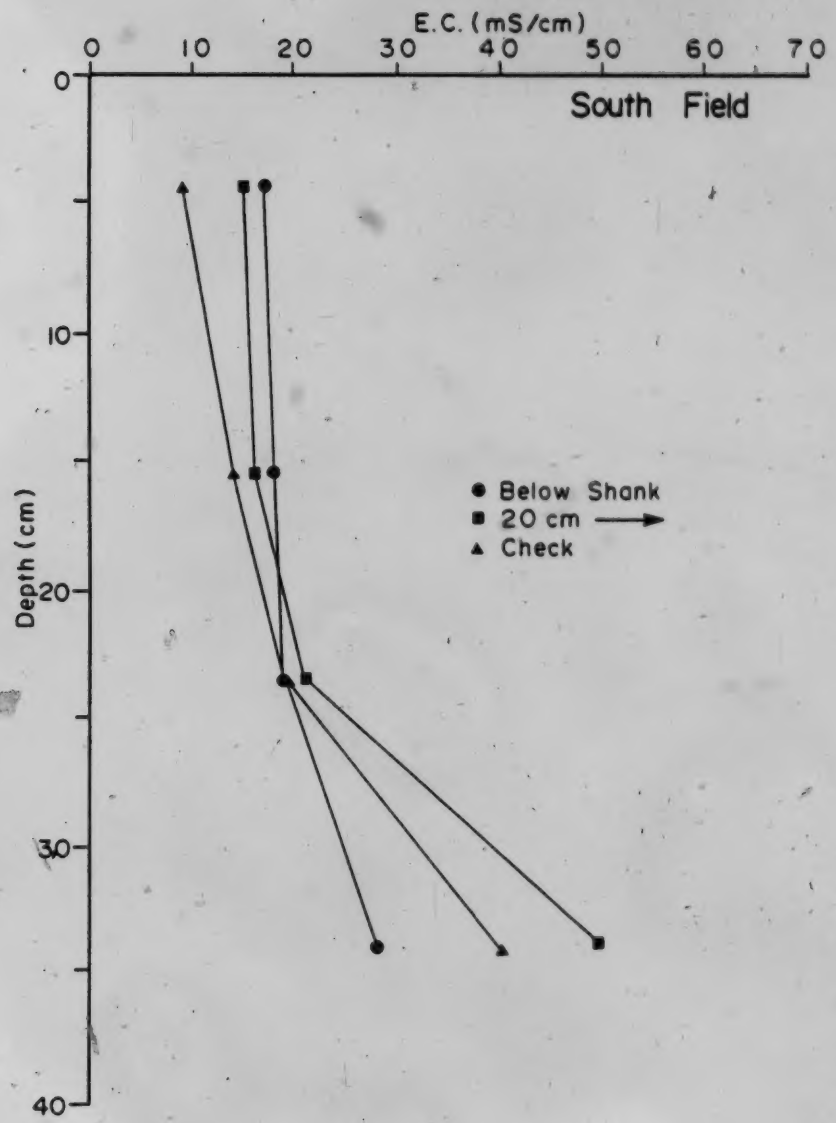


Figure 11. Electrical conductivity (EC) vs depth for ripping treatments (South Field).

three treatments showed treatment effects to be nonsignificant at the 0.05 level for both fields (Tables 1 and 5). Treatment effects were significant, however, at the 0.07 level for both fields. The treatment-depth interaction was highly significant in the South Field (Table 5). Multiple mean comparisons showed the below shank treatment mean to be different from those of the other two treatments in the lowest horizon (Table 10).

Once again, an examination of measures of dispersion (standard deviation and range) point to the existence of greater variability in the EC data from the North Field than from the South Field (Tables 8 and 10). As was the case with the SAR data, reasons for this contrast are assumed to be related to shank spacing and sampling procedures.

Electrical conductivity values in the deep plowed plot were higher but paralleled those of the 20 cm $\longrightarrow$ sampling locations in the North Field (Figure 10). Little difference existed between the four treatments in the upper horizon, but EC values increased noticeably particularly for deep plowed and 20 cm $\longrightarrow$ treatments in the lower two horizons. Statistical analysis based on four treatments and four depths, with no replication partitioned out, indicated that the treatment effects in the North Field were significant (Table 2). Multiple mean comparisons, using the least significant difference test, confirmed that the deep plowed treatment mean was different from the check and below shank means (Table 9). The comparisons also showed differences between the 20 cm $\longrightarrow$ treatment mean and the check mean (Table 9).

Table 8. Electrical conductivity measurements for saturation extracts from samples taken from check, below shank, 20 cm ⟶ and deep plowed areas (North Field).

Treatment	Range[1]	Mean	Standard Deviation
Ap Horizon (0-8.5 cm)			
Check	0.40-1.2	0.81	0.28
Below Shank	0.51-2.0	0.99	0.57
20 cm ⟶	0.36-1.7	1.0	0.54
Deep Plowed	0.92-1.4	1.2	0.16
Bnt Horizon (8.5-22.5 cm)			
Check	0.26-1.8	1.1	0.54
Below Shank	0.25-2.6	1.4	0.84
20 cm ⟶	0.24-3.0	1.2	1.00
Deep Plowed	1.20-3.4	1.9	0.73
B-C Horizon (22.5-27.5 cm)			
Check	1.20-2.3	1.7	0.50
Below Shank	0.43-3.6	1.9	1.00
20 cm ⟶	0.49-6.9	2.8	2.20
Deep Plowed	1.50-4.4	2.4	0.98
Csk Horizon (27.5-40 cm)			
Check	0.94-6.9	2.5	2.2
Below Shank	0.39-7.4	3.5	2.6
20 cm ⟶	0.33-7.2	4.3	2.6
Deep Plowed	2.10-7.5	5.4	1.8

[1] Seven replicates.

Table 9. Multiple mean comparisons for treatment means for EC data using least significant difference test (North Field).

Treatment	Mean
Check	1.5 a[1]
Below Shank	1.9 ab
20 cm ⟶	2.3 bc
Deep Plowed	2.7 c

[1] Means not followed by same letter are statistically different according to LSD test ($p \leq 0.05$).

Table 10. Electrical conductivity measurements for saturation extracts from samples taken from check, below shank, and 20 cm ⟶ areas (South Field).

Treatment	Range[1]	Mean[2]	Standard Deviation
Ap Horizon (0-8.5 cm)			
Check	0.62-1.2	0.91a	0.21
Below Shank	1.00-2.6	1.7a	0.49
20 cm ⟶	0.88-2.3	1.5a	0.44
Bnt Horizon (8.5-22.5 cm)			
Check	0.89-2.0	1.4a	0.46
Below Shank	1.30-2.3	1.8a	0.43
20 cm ⟶	0.84-2.4	1.6a	0.51
B-C Horizon (22.5-27.5 cm)			
Check	1.6-2.4	1.9a	0.47
Below Shank	1.6-2.4	1.9a	0.36
20 cm ⟶	1.6-3.2	2.1a	0.54
Csk Horizon (27.5-40 cm)			
Check	1.6-7.2	4.0a	2.4
Below Shank	1.7-4.5	2.8b	1.2
20 cm ⟶	2.8-6.6	5.0a	1.4

[1] Seven replicates.

[2] Means not followed by same letter within each depth are statistically different according to LSD test ($p \leq 0.05$).

4.1.3 pH

Another important soil chemical parameter which was assessed during this investigation was pH. The measurements were not done on saturation extracts, but rather on 1:2.5 soil water slurries (Figures 12 and 13, Tables 11 and 12). An analysis of variance for ripped plots in the North Field, based on three treatments, four depths and seven replicates, indicate that the treatment effect and the treatment-depth interaction are not significant (Table 1). A similar analysis of variance of pH data for samples taken from the South Field reveal the treatment-depth interaction to be significant (Table 5). Multiple mean comparisons, using the least significant difference test on treatment-depth interaction means, showed the below shank treatment to be significantly higher than both the 20 cm $\longrightarrow$ and check means in the upper two horizons (Table 12).

As in the previous cases of SAR and electrical conductivity data, the results of pH investigations on the deep plowed plot in the North Field are plotted on the same graph as the ripping data (Figure 12). A comparison of the ripped treatment means to the deep plowed treatment means reveals an obvious contrast between the two tillage methods. Analysis of variance, based on four treatments and four depths, showed a highly significant treatment-depth interaction (Table 2). Multiple mean comparisons of treatment-depth means showed deep plowing means to be significantly higher than the other three treatments at depths one and two (Table 11).

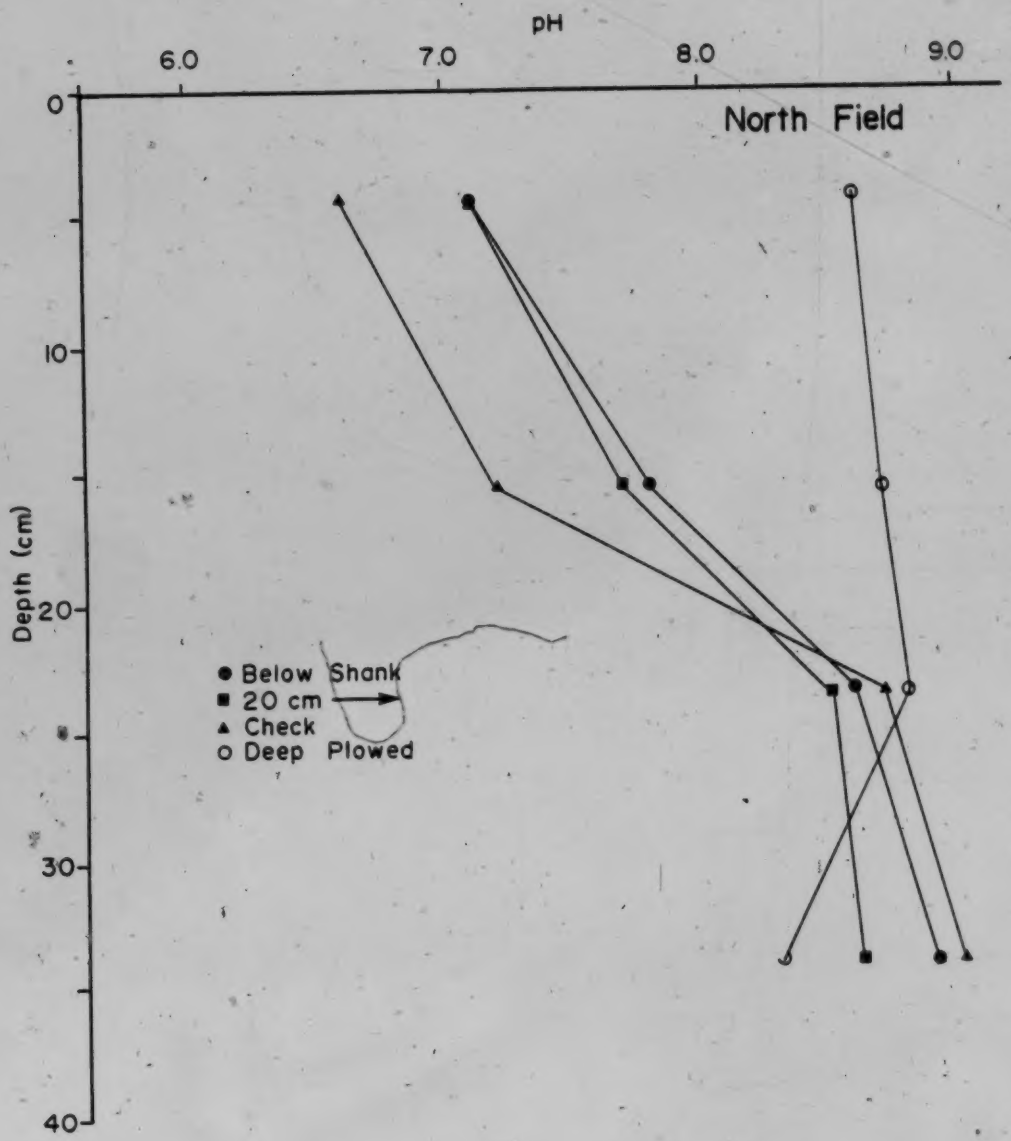


Figure 12. pH vs depth for ripping and deep plowing treatments (North Field).

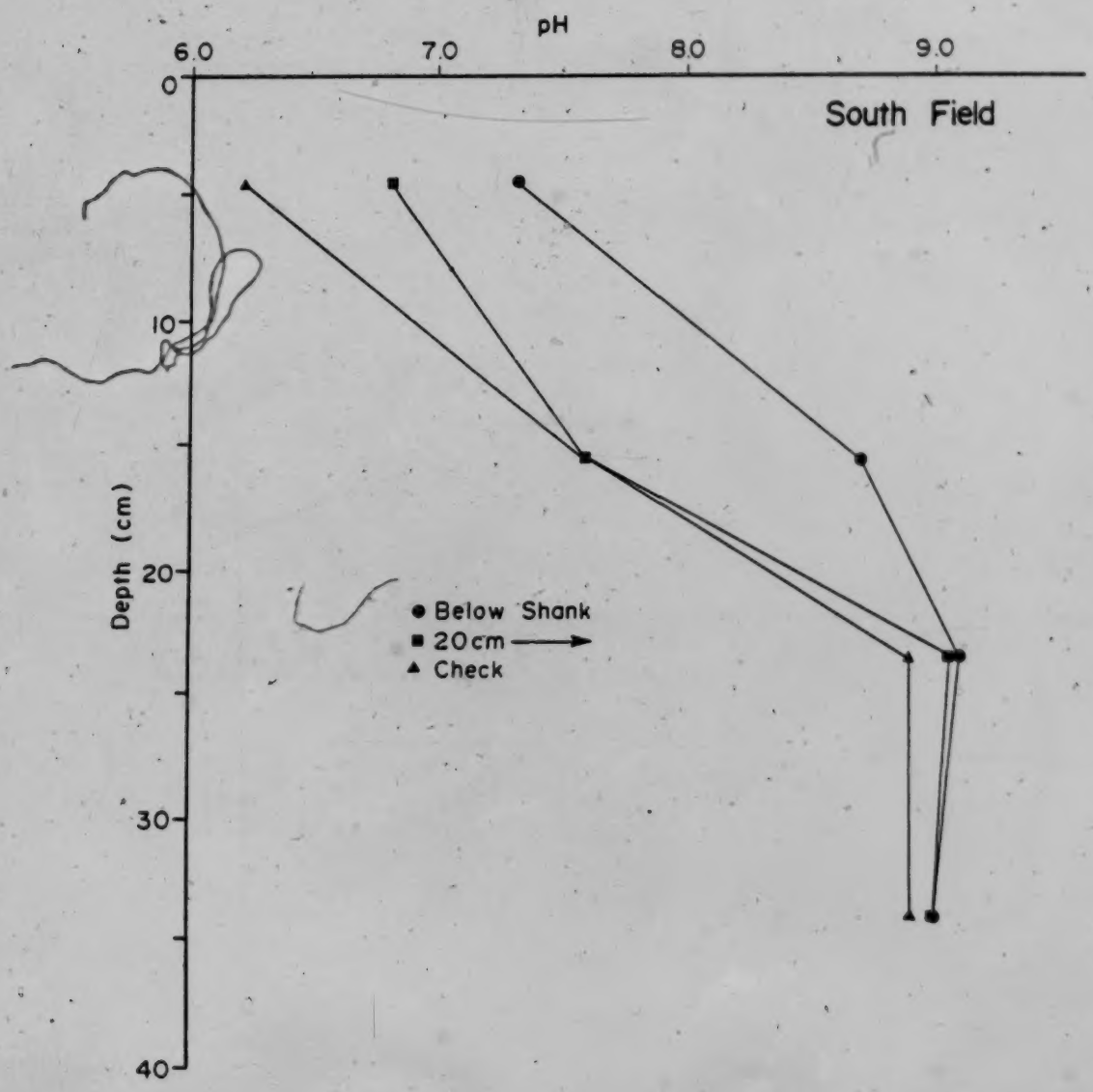


Figure 13. pH vs depth for ripping treatments (South Field).

Table 11. pH values of soil samples taken from check, below shank, 20 cm ⟶ and deep plowed areas (North Field).

Treatment	Range[1]	Mean[2]	Standard Deviation
Ap Horizon (0-8.5 cm)			
Check	5.7-7.9	6.6a	0.72
Below Shank	6.2-8.4	7.1a	0.98
20 cm ⟶	6.0-8.4	7.1a	0.98
Deep Plowed	8.0-8.9	8.6b	0.32
Bnt Horizon (8.5-22.5 cm)			
Check	6.0-8.0	7.2a	0.79
Below Shank	6.2-8.9	7.8a	0.99
20 cm ⟶	6.3-8.9	7.7a	0.98
Deep Plowed	7.8-9.2	8.7b	0.46
B-C Horizon (22.5-27.5 cm)			
Check	8.1-9.4	8.7a	0.58
Below Shank	7.1-9.3	8.6a	0.84
20 cm ⟶	7.4-9.2	8.5a	0.60
Deep Plowed	8.1-9.2	8.8a	0.36
Csk Horizon (27.5-40 cm)			
Check	7.5-9.4	9.0a	0.64
Below Shank	8.4-9.4	8.9a	0.45
20 cm ⟶	8.1-9.6	8.6a	0.54
Deep Plowed	7.7-8.8	8.3a	0.33

[1] Seven replicates.

[2] Means not followed by same letter within each depth are statistically different according to LSD test ($p \leq 0.05$).

Table 12. pH values of soil samples taken from check, below shank, and 20 cm ⟶ areas (South Field).

Treatment	Range[1]	Mean[2]	Standard Deviation
Ap Horizon (0-8.5 cm)			
Check	5.9-6.5	6.2a	0.20
Below Shank	6.9-8.0	7.3b	0.41
20 cm ⟶	6.2-7.6	6.8a	0.55
Bnt Horizon (8.5-22.5 cm)			
Check	6.3-8.8	7.6a	1.00
Below Shank	7.0-9.3	8.7b	0.77
20 cm ⟶	6.1-8.7	7.6a	1.10
B-C Horizon (22.5-27.5 cm)			
Check	8.6-9.4	8.9a	0.44
Below Shank	8.3-9.5	9.1a	0.44
20 cm ⟶	8.8-9.4	9.1a	0.24
Csk Horizon (27.5-40 cm)			
Check	8.1-9.3	8.9a	0.51
Below Shank	8.7-9.3	9.0a	0.29
20 cm ⟶	8.6-9.4	9.0a	0.28

[1] Seven replicates.

[2] Means not followed by same letter within each depth are statistically different according to LSD test ($p \leq 0.05$).

4.2 DISCUSSION (CHEMISTRY)

In considering tillage-soil chemistry relationships, single bottom deep plowing is the most drastic treatment possible. It completely inverts the soil profile lifting salt enriched parent material to the surface and burying most of the Ap horizon. Salts are physically moved upwards and then exposed to normal transfers and translocations inherent in ongoing soil genesis. This being the case, results from fields exposed to single bottom deep plowing could be thought to represent the maximum possible change in soil chemical properties as caused by physical lifting of salts. Results of changes in SAR, EC and pH created by single bottom deep plowing are the most dramatic in this study and will be used as the benchmark for change caused by physical lifting of salts.

4.2.1 Deep Plowing (North Field)

Statistically significant increases in pH and EC in the two surface horizons and a statistically significant reduction in SAR occurred throughout the profile for the deep plowed treatment (Figure 12, 10 and 8, respectively). This agrees with previous findings in the literature (Harker et al. 1977, Cairns and Lavado 1981, Ballantyne 1983). Physical lifting of calcium, magnesium and sodium carbonates would appear to be the cause of the increases in pH and EC in the upper two horizons. The general reduction in SAR would be caused by a more homogeneous mixing of calcium carbonate and calcium sulfate salts throughout the profile.

4.2.2 Ripping (North Field)

Changes in soil chemistry associated with ripping in the North Field (narrow shank spacing) are much less than in the South Field. There were no significant differences between chemical properties (SAR, EC and pH) of samples taken from the check and disturbed areas (below shank and 20 cm ⟶). Soil pH is increased by half a unit in the upper two horizons of the disturbed areas (below shank and 20 cm ⟶) relative to the undisturbed check. The magnitude of this increase is small compared to that associated with deep plowing (1.5-2 pH units) so appreciable physical lifting of salts is not a probable explanation.

Anion composition in the upper two horizons of the three treatments in the north field (see Appendix 1) reveals that samples from the disturbed area (below shank and 20 cm ⟶) are more likely to be dominantly bicarbonate than those of the undisturbed check, which are dominantly sulfate. Equilibrium bicarbonate solutions have higher pH values than equilibrium sulfate solutions (Hrasko 1971).

A possible explanation for the bicarbonate dominance in the disturbed ripping treatments would be upward movement of highly mobile bicarbonates, probably accompanied by sodium, through capillary action. Moisture is able to penetrate the disrupted Bnt in below shank and 20 cm ⟶ areas and the salt enriched B-C and Csk horizons. This moisture then becomes perched at the end of macropores or fractures created by ripping and, as saturation is reached, salts dissolve. With the advent of drying the moisture moves upwards or laterally in response to matric potential gradients

through micropores. Accompanying the moisture would be highly mobile sodium and bicarbonate ions. Groundwater above 70 m in the study area is dominated by carbonate and bicarbonate anions (Le Breton 1971) so it is possible additional bicarbonate could be coming from this source. Depth to the permanent water table in the study area is unknown. Movement of sodium bicarbonates accompanying groundwater through capillarity in response to matric potential gradients has been documented by several authors (Landsburg 1981; Szabolcs and Lestak 1967). It should be noted that not enough sodium, or total salt, was moved to significantly increase the SAR or EC in surface horizons.

Another trend, which is not statistically significant, appearing in the ripping data from the North Field is a slight increase in EC in the 20 cm $\longrightarrow$ area for the lower two horizons. This could also be explained by increased moisture penetrating the shank track and then slowly moving salts laterally. This is in agreement with work done in South Dakota which showed that infiltrating water redistributed salt towards undisturbed zones between shank tracks although statistics were not presented (White et al. 1981). Logically, this would cause a depletion in EC in the below shank region relative to the undisturbed check, but this does not appear to be the case.

4.2.3 Ripping (South Field)

In contrast to results obtained from ripping treatments in the North Field, statistically significant alterations in SAR, EC and pH occurred in the South Field. Increased sodium and bicarbonate levels

in the upper two horizons of the below shank area (see Appendix 1) cause statistically higher SAR and pH values. Soil pH values are increased by one unit in the below shank areas relative to the undisturbed check in the upper two horizons. Although this increase is more dramatic than that seen in the below shank area in the North Field, it is not as dramatic an increase as occurred at the surface with single bottom deep plowing. However, the increase in pH in the second horizon (Bnt) from the check to the below shank area is similar to that obtained from deep plowing over the check in the North Field. This would seem to suggest a combination of physical lifting and upward movement of salts due to capillary action.

Physical lifting of calcium, magnesium, and sodium carbonate salts from the Csk horizon to the Bnt horizon would explain the dramatic increase in pH observed in the second horizon of the below shank area. This would also agree with results of the particle size investigation which show a displacement of clay from the Csk to the Bnt horizon in the below shank area (see Figure 19).

After the initial physical disruption, infiltrating snowmelt and rainfall would become the major forces for redistributing salts in the below shank and 20 cm $\longrightarrow$ areas. Samples were taken three years after ripping was completed, meaning that soils in the below shank area were subjected to numerous wetting and drying cycles caused by rainfall, three successive wheat crops, and three successive snowmelts. Variations in soil moisture with time and depth in the below shank, 20 cm $\longrightarrow$ and check areas for the growing season of 1983 are presented in the moisture results section.

A scenario similar to that described for ripping in the North Field is postulated. After major rainfall events, water percolates rapidly to the depth of ripping (35–40 cm) in the below shank area and becomes perched on the undisturbed saline-sodic parent material. Saturated conditions develop, if sufficient moisture is supplied, and readily soluble salts are taken into solution. At the onset of drying, moisture can move laterally to the drier adjacent soil outside the disturbed shank track and upwards through micropores in response to a gradient caused by evaporation and crop growth. Moving with the moisture would be readily soluble salts, such as sodium bicarbonate.

Evidence for upward movement of sodium bicarbonate in the below shank areas in the South Field is seen in the higher SAR, pH and EC values in the upper two horizons (Figures 9, 13 and 11). Physical lifting of less soluble calcium salts does not occur. Further evidence of salts being redistributed laterally at depth is seen by the statistically significant increase in EC at the 20 cm $\longrightarrow$ location in the lowest horizon (Figure 11). At this depth the below shank region appears depleted of salts which have moved sideways to the 20 cm $\longrightarrow$ location. Once again, this concurs with the findings of White et al. (1981).

4.3 RESULTS (MOISTURE)

Statistical analysis of the moisture data was based on a factorial design with seven replicates, three treatments, eight depths and seven weeks (Table 13).

Table 13. Analysis of variance for moisture data from ripping treatments (South Field).

Source of Variation	df	SS	MS	f-ratio	Sign
Replicates	6	1,480.1	246.7	45.47	**
Depth	7	10,181.1	1,454.4	14.0[1]	**
Weeks	6	3,603.9	600.6	5.77[1]	**
Treatment	2	2,448.6	1,224.3	11.8[1]	**
Depth x Weeks	42	5,286.5	125.9	10.9	**
Depth x Treatment	14	1,741.0	124.4	10.8	**
Treatments x Weeks	12	531.0	44.2	3.85	**
Depth x Weeks x Treatment	84	1,038.2	12.35	1.07	NS
Error	1,002	11,514.4	11.49		

1 Valid error term for main effects (depth, weeks, treatment) is a combination of three significant double interactions:

$$VE = \frac{(D \times W) + (D \times T) + (T \times W)}{df(D \times w) + df(D \times T) + df(T \times W)}$$

$$VE = \frac{5286.5 + 1741.0 + 531.0}{42 + 14 + 12}$$

$$VE = 111.15$$

Selection of the appropriate error mean square for the f-ratios was according to Zalik (1981). Multiple mean comparisons of treatment means, using the Least Significant Difference test, showed all three treatments to be different from each other (Table 14).

Table 14. Multiple mean comparisons for treatment means for moisture data using least significant difference test (South field).

Treatment	Mean[1]
Check	14.0c
Below Shank	17.6a
20 cm ⟶	15.7b

[1] Means not followed by the same letter are statistically different according to Least Significant difference test.

4.4 DISCUSSION (MOISTURE)

Moisture content did not vary to any great extent between the check, 20 cm ⟶ and below shank sampling locations for the 0-5 cm or 5-10 cm depths (Figure 14). This was to be expected because the average depth of the Ap horizon was 8.5 cm. This means that the

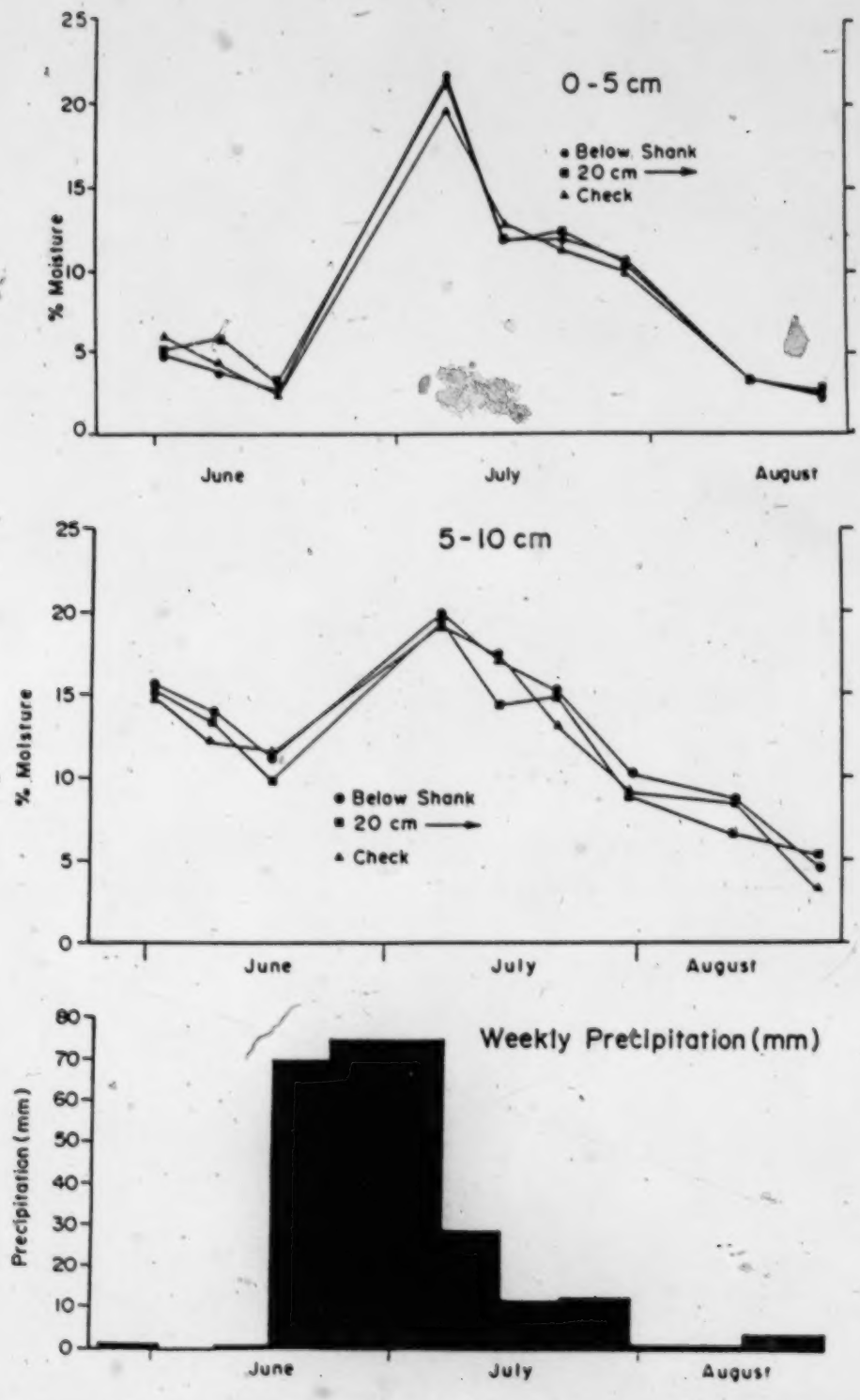


Figure 14. % moisture vs time, with weekly precipitation data, for ripping treatments at 0-50 cm and 5-10 cm depths (South Field).

majority of samples were being taken from the loose, granular surface horizon at all sampling locations. Normal tillage operations loosen this horizon regularly, thus making it receptive to infiltration and percolation of moisture. The impact of the ripper shank at this depth is negligible.

An interesting and noteworthy trend in the data from this investigation is the increase in moisture content in the 20 cm $\longrightarrow$ sampling location during the period from July 14 to July 21, at the 5-10 cm depth. This slight increase is in sharp contrast to the marked decrease in moisture content found at the other sampling locations (check and below shank) for this time period. Similar trends exist at the 10-15 cm and 15-20 cm depth (Figure 15). One could speculate that this occurrence was caused by the lateral movement of water from moister, below shank areas to drier areas adjacent to the disturbed zone.

Major differences between the three treatments at the 10-15 and 15-20 cm depths occurred during major rainfall in June 1983 (Figure 15). At these two depths, the below shank and 20 cm $\longrightarrow$ areas showed increased moisture accumulation compared to the check, particularly at the 15-20 cm depth. The effect of the ripper shank slicing through the Bnt horizon and the resultant disruption and shattering from this operation heightened moisture accumulation at these depths. Moisture hindered from downward movement in the check penetrated the Bnt horizon in the disturbed shank area through macropores created by ripping.

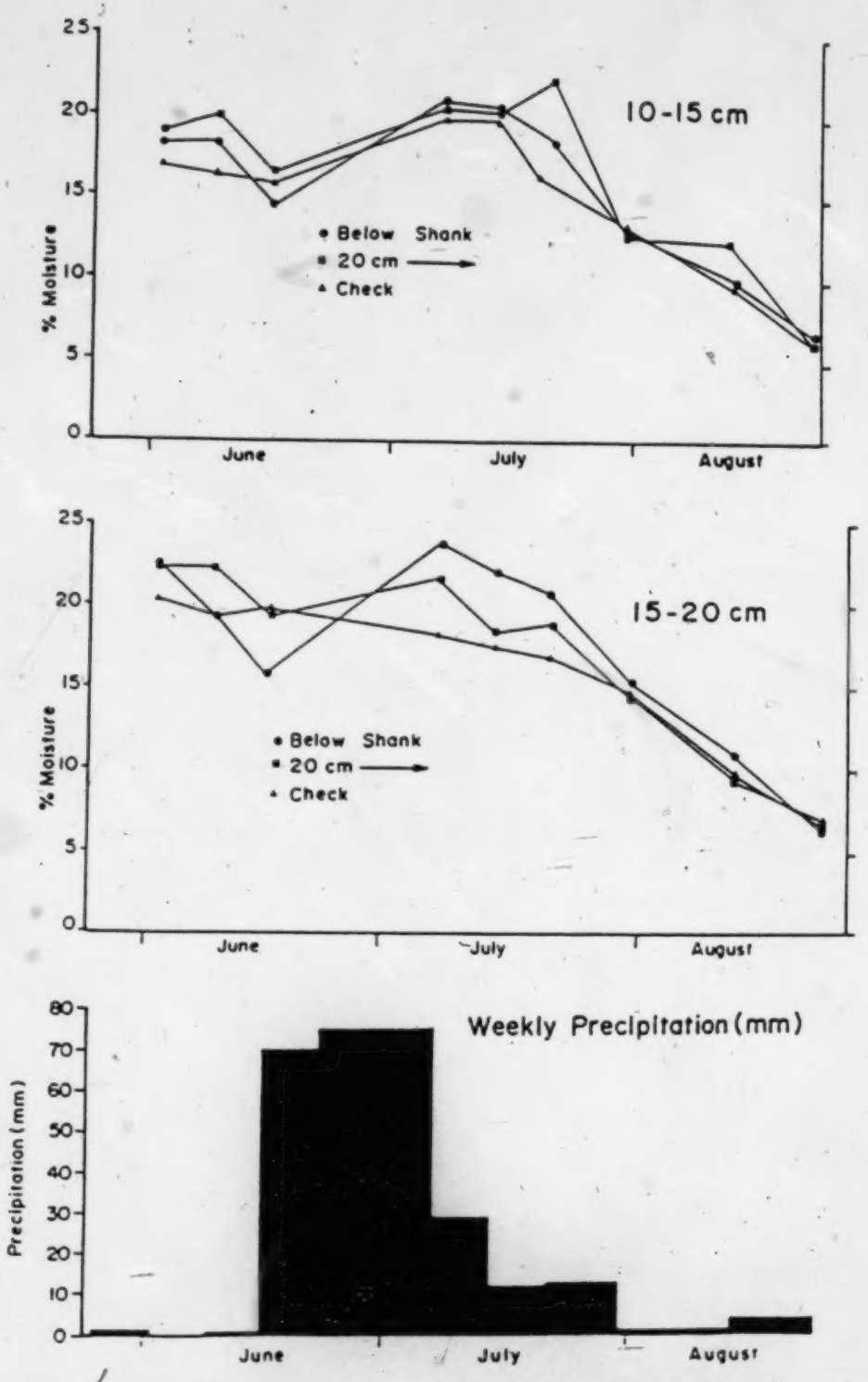


Figure 15. % moisture vs time, with weekly precipitation data, for ripping treatments at 10-15 cm and 15-20 cm depths (South Field).

Another trend at the 10-15 and 15-20 cm depths is the tendency towards greater moisture content in the 20 cm ⟶ treatment than in the below shank treatment during the two weeks (June 2 to June 16) preceding the major rainfall (Figure 15). A possible explanation for this phenomenon is that during this time period, the soil experienced another drying cycle. After having been wetted by the springmelt or previous rainfallduring early spring, it underwent a process of lateral water movement from the below shank to the 20 cm ⟶ areas during the two weeks before the large rainfall. This trend is similar to that which developed, as previously mentioned, in the 5-10, 10-15 and 15-20 cm depths between July 14 and July 21. Also, plant roots may have removed moisture more readily from below the shank than 20 cm to one side. One further point of interest with reference to this data is that at the 15-20 cm depth, the check treatment showed no response to rainfall. This indicates that little or no moisture penetrated beyond 15 cm in the non-ripped area.

There was a continuation of the trend whereby moisture content at the 20-25 and 25-30 cm depths increased in the below shank area after a heavy rainfall (Figure 16). Once again, the check treatment showed no response during this period. The below shank area moistened quite rapidly at the onset of rainfall, and remained substantially moister than the check and 20 cm ⟶ areas until mid-August. Rapid wetting in the narrow slot created by ripping at these depths (20-30 cm) has also been noted by Hauser and Taylor (1964). In the 20 cm ⟶ location, there was a modest response to rainfall at the 20-25 cm depth, but beyond this depth (Figure 16) increases in

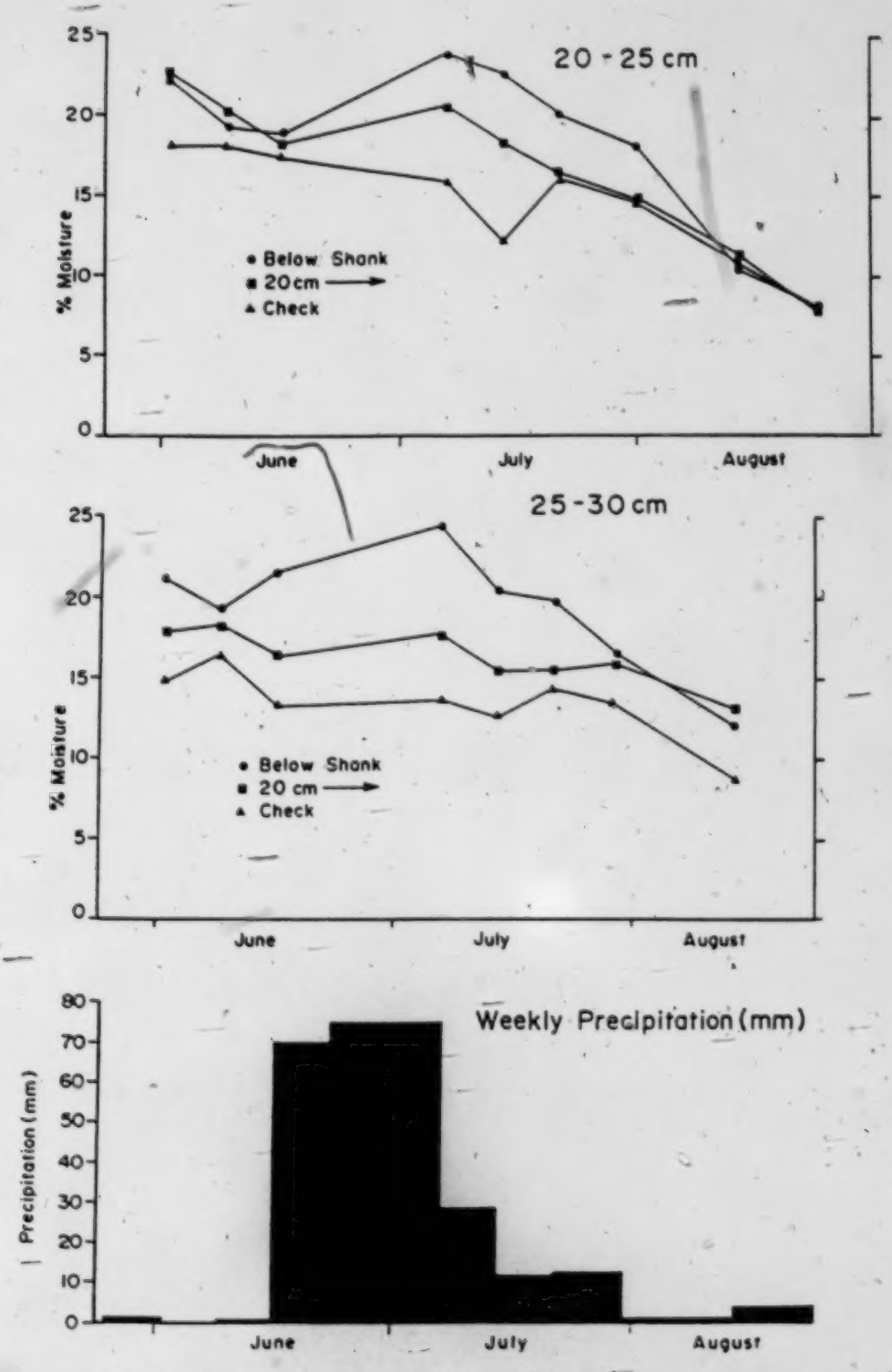


Figure 16. % moisture vs time, with weekly precipitation data, for ripping treatments at 20-25 cm and 25-30 cm depths (South Field).

moisture content after the rain were slight. There was no delayed increase in moisture content at these depths following substantial rainfall, as was the case at the 5-10, 10-15 and 15-20 cm depths.

At these two depths (20-25 cm and 25-30 cm), the below shank and 20 cm ⟶ treatments are wetter than the check area from the onset of the study. The three treatments converge to similar moisture contents (8-10%) by the end of the growing season at the 20-25 cm depth. Below this depth the below shank and 20 cm ⟶ treatments remain moister relative to the check throughout the period of the study. This might suggest the influence of plant roots is greatest up to a depth of 25 cm and at greater depths the additional moisture present late in the growing season is not being utilized.

Increased moisture penetration in the below shank area is also evident at the 30-35 cm and 35-40 cm depths (Figure 17). The below shank treatment is moister throughout the growing season and still shows a response to rainfall at these depths. Of note is the fact that moisture content in the below shank and 20 cm ⟶ areas increases quite substantially relative to the check during the first week (June 7 to June 14) of the study at these depths (Figure 17). This is not in response to rainfall and comes at a time when moisture content is decreasing or remaining constant at other depths. A possible explanation for this is moisture from a gradual springmelt moving slowly downward in the profile, in the disturbed areas.

In regards to the 15-40 cm depths in the below shank and 20 cm ⟶ areas, there is significantly more moisture than in the check for crop growth after substantial rainfalls (Figures 15, 16, and 17).

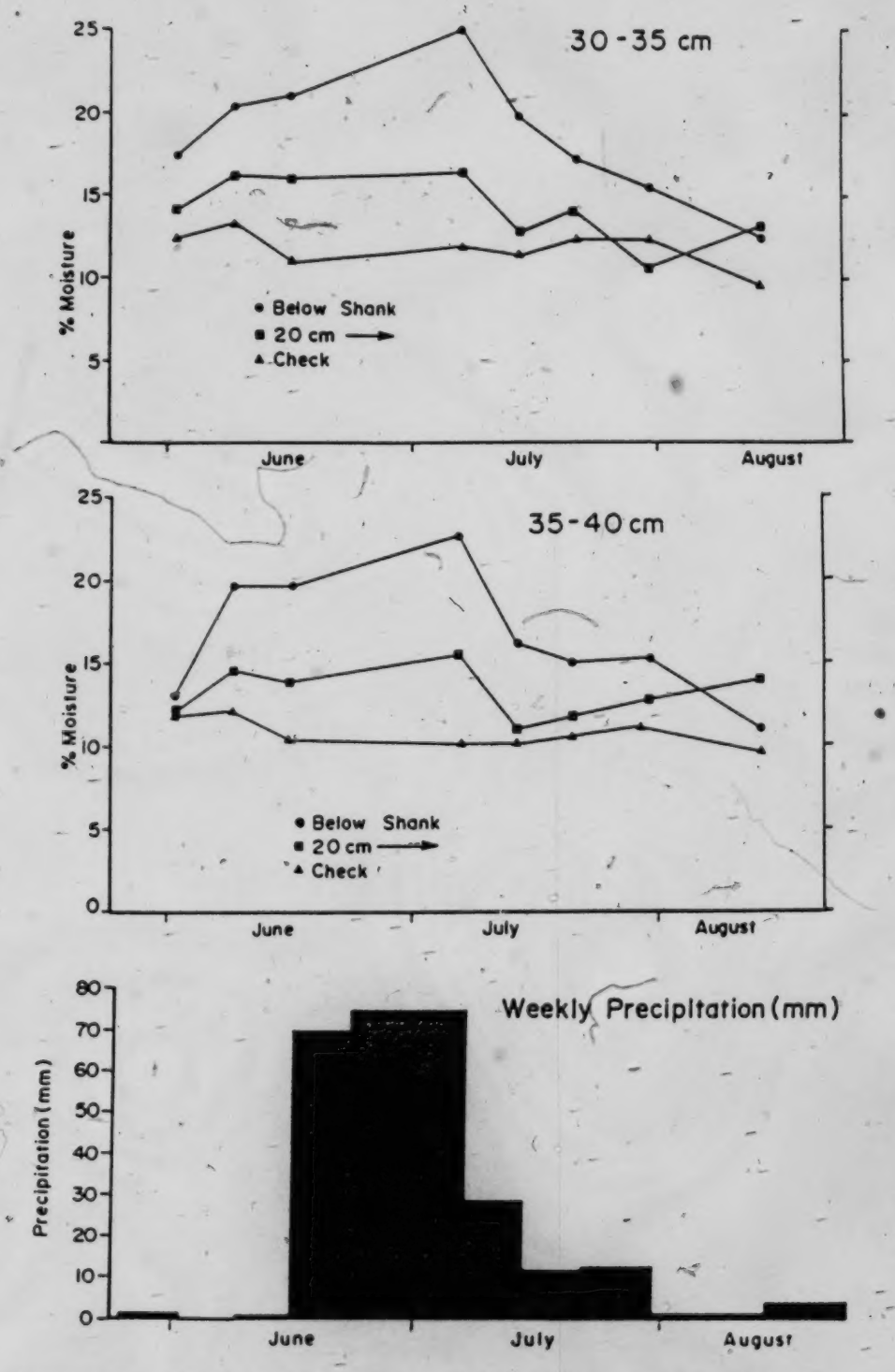


Figure 17. % moisture vs time, with weekly precipitation data, for ripping treatments at 30-35 cm and 35-40 cm depths (South Field).

This is in agreement with the findings of other researchers who found ripping increased moisture penetration and storage in the disturbed area around the shank (White et al. 1981 and Hauser and Taylor 1964). There is more moisture in the below shank area than in the 20 cm ⟶ location. More vigorous crop growth in these regions (Plate 4) leads to greater use of moisture during the peak growing period from mid-July onwards, as evidenced by the sharp declines in moisture content after July 7. The exception to this case occurs at the end of the growing season when the moisture content increases slightly into the 20 cm ⟶ location at the 30-35 cm and 35-40 cm depths. This could be caused by water moving laterally from moister below shank areas to drier 20 cm ⟶ areas. This would agree with results in the chemistry investigation which show higher concentrations of salt at the 20 cm ⟶ location in the lowest horizon (Figure 11).

4.5 RESULTS (PARTICLE SIZE DISTRIBUTION)

The distribution of clay with depth for the ripping treatments in the North and South Fields is illustrated in Figures 18 and 19, respectively. Complete data for particle size distribution, with all three size fractions represented, for both fields is presented in Tables 15 and 16. Clay was chosen out of the three size fractions for graphing and statistical analyses because of its major influence on soil moisture and tilth properties.

Ripping in the North Field, with the narrow (56 cm) shank spacings, has done very little to alter clay distribution in the profile (Figure 18). Analysis of variance, based on seven

Plate 4. Uneven crop growth present in South Field. Greener crop with increased height centered over "below shank" area.

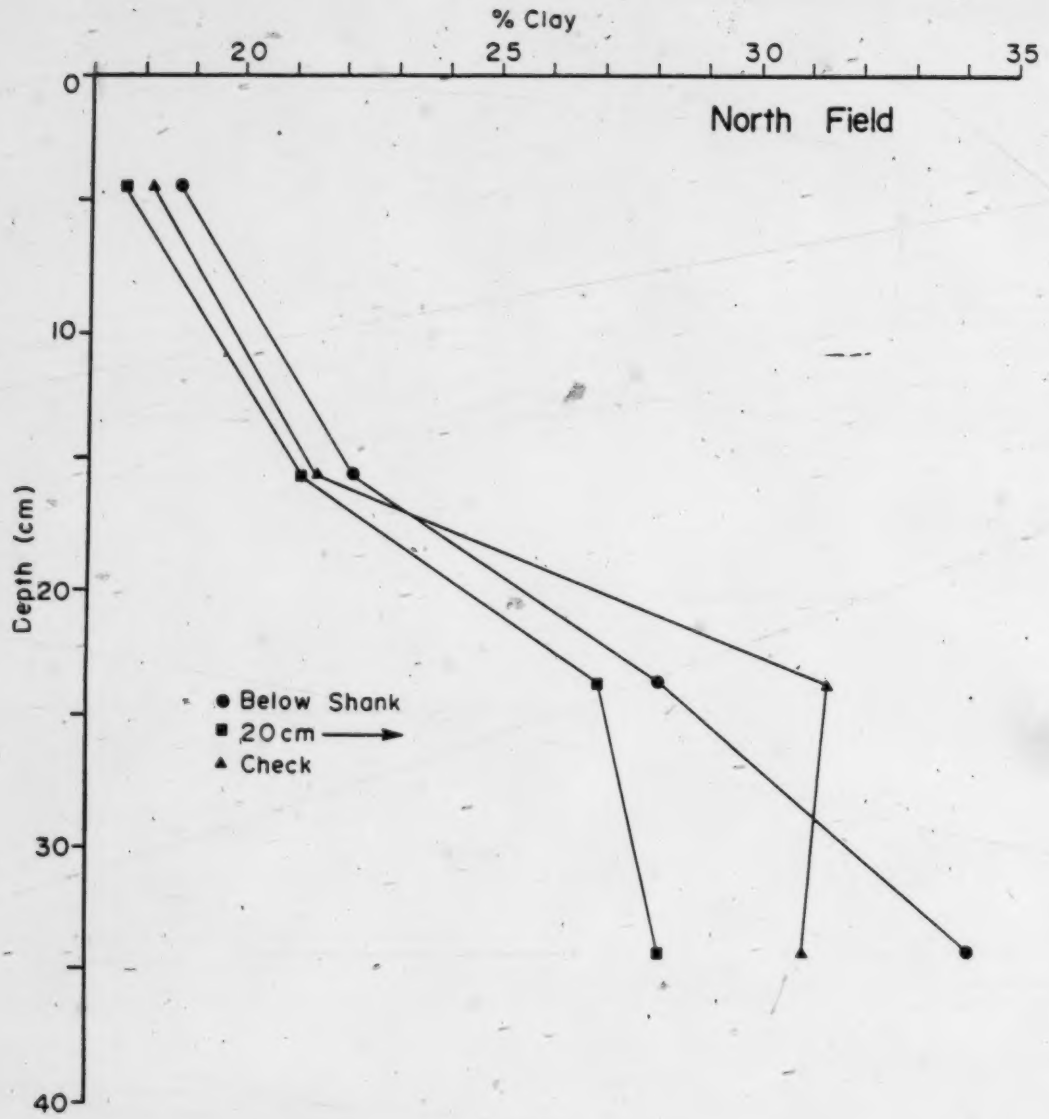


Figure 18. % clay vs depth for ripping treatments (North Field).

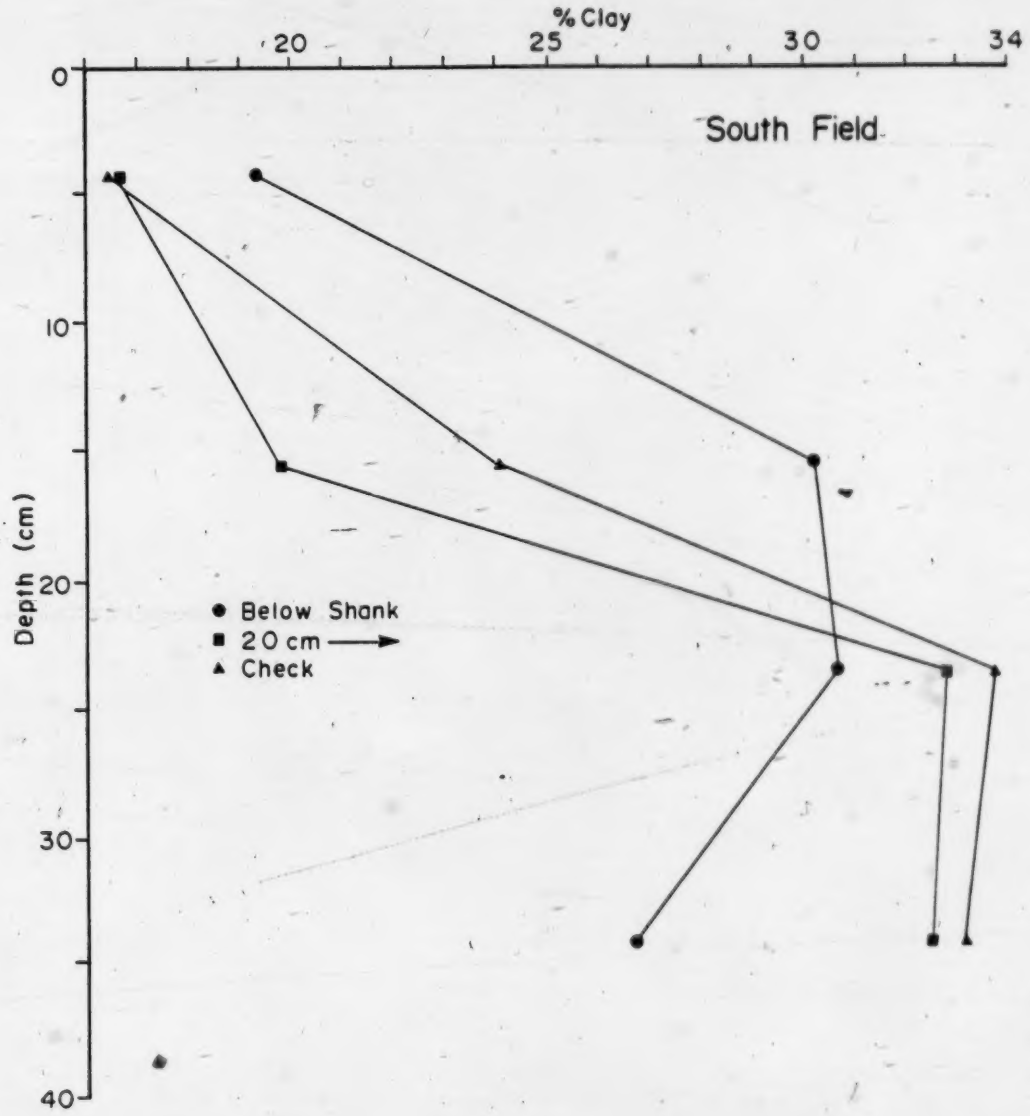


Figure 19. % clay vs depth for ripping treatments (South Field).

Table 15. Particle size and available moisture percentage for ripping samples (North Field).

	% Sand[1]	% Silt[1]	% Clay[1]	CSSC Texture[2]	33 kPa[3]	1500 kPa[4]	Available Water %[5]
Check							
0–8.5 cm	49	33	18	L	22	12	10
8.5–22.5 cm	51	27	22	SCL	24	12	12
22.5–27.5 cm	41	27	32	CL	26	15	11
27.5–40 cm	43	26	31	CL	28	14	14
Below Shank							
0–8.5 cm	51	30	19	L	24	12	12
8.5–22.5 cm	47	31	22	L	22	13	9
22.5–27.5 cm	40	31	29	CL	31	18	13
27.5–40 cm	37	19	34	CL	25	15	10
20 cm ⟶							
0–8.5 cm	52	30	18	L	23	11	12
8.5–22.5 cm	48	30	22	L	26	14	12
22.5–27.5 cm	45	28	27	L	28	14	14
27.5–40 cm	39	33	28	L	25	13	12

1 Values reported are means of seven replicates.
2 Textural classification according to Canadian System of Soil Classification.
3 Percent moisture at 33 kPa tension for single sample having clay content nearest to mean for that depth.
4 Percent moisture at 1500 kPa tension for single sample having clay content nearest to mean for that depth.
5 Available water % = percent moisture at 33 kPa tension - percent moisture at 1500 kPa tension.

Table 16. Particle size and available moisture percentage for ripping samples (South Field).

	% Sand[1]	% Silt[1]	% Clay[1]	CSSC Texture[2]	33 kPa[3]	1500 kPa[4]	Available Water %[5]
Check							
0-8.5 cm	53	31	16	SL	21	8	13
8.5-22.5 cm	49	27	24	SCL	30	16	14
22.5-27.5 cm	40	27	34	CL	33	18	15
27.5-40 cm	37	29	33	CL	33	20	13
Below Shank							
0-8.5 cm	51	28	19	L	21	9	12
8.5-22.5 cm	43	26	30	CL	32	16	16
22.5-27.5 cm	41	29	30	CL	37	24	13
27.5-40 cm	44	30	27	L	32	15	17
20 cm ⟶							
0-8.5 cm	54	30	17	SL	21	9	12
8.5-22.5 cm	48	29	20	L	26	13	13
22.5-27.5 cm	41	27	33	CL	37	18	19
27.5-40 cm	39	28	32	CL	34	19	15

1 Values reported are means of seven replicates.
2 Textural classification according to Canadian System of Soil Classification.
3 Percent moisture at 33 kPa tension for single sample having clay content nearest to mean for that depth.
4 Percent moisture at 1500 kPa tension for single sample having clay content nearest to mean for that depth.
5 Available water % = percent moisture at 33 kPa tension - percent moisture at 1500 kPa tension.

replicates, four depths and three treatments, showed neither the treatment effect or the treatment-depth interaction to be significant (Table 18). The only noticeable trend occurring is in the lower two horizons where clay levels in the 20 cm ⟶ area are somewhat depleted and clay appears to have been displaced downwards in the below shank area (Figure 18).

Ripping in the South Field, with wide (112 cm) shank spacings, appears to have caused upward movement of clay in the profile (Figure 19). Similar analysis of variance as performed on data from the North Field showed a non-significant treatment effect, but a highly significant treatment x depth interaction (Table 17). Least significant difference tests on the treatment x depth interaction means showed the elevated clay levels in the second horizon of the below shank area to be different from those of the check and 20 cm ⟶ areas (Table 20). Similar tests also showed the depleted clay levels in the bottom horizon of the below shank area to be different from those of the check and 20 cm ⟶ areas (Table 20).

In addition to particle size distribution, another physical property investigated was available moisture ranges. Results of this inquiry are presented in Tables 15 and 16, for the north and south fields respectively. No statistics were performed on this data because only a single sample from each treatment-depth combination was analyzed.

Available water percentages show very little variation between treatments in the north field (Table 15). This concurs with results of the particle size investigation which show only slight differences

Table 17. Analysis of variance for percent clay - from Ripping treatments (South Field).

Source of Variation	df	SS	MS	f-ratio	Sig.
Replicates	6	503.8	84.0	5.68	**
Depth	3	2,760.1	920.0	62.3	**
Treatment	2	3.64	1.82	0.12	NS
Depth x Treatment	6	421.4	70.2	4.75	**
Error	62	915.0	14.8		

NS = Not Significant.
* = Significant ($p \leq 0.05$).
** = Significant ($p \leq 0.01$).

Table 18. Analysis of variance for percent clay - from Ripping treatments (North Field).

Source of Variation	df	SS	MS	f-ratio	Sig.
Replicates	6	400.0	66.6	3.40	**
Depth	3	2,280.9	760.3	38.8	**
Treatment	2	90.6	45.3	2.31	NS
Depth x Treatment	6	124.1	20.7	1.05	NS
Error	65	1,273.5	19.6		

NS = Not Significant.
** = Significant ($p \leq 0.01$).

Table 19. Percent clay for samples taken from below shank, 20 cm ⟶, and check areas (North Field).

	Range[1]	Mean	Standard Deviation
Ap Horizon (0-8.5 cm)			
Check	11-25	18.1	4.8
Below Shank	15-23	18.7	3.4
20 cm ⟶	13-22	17.6	3.1
Bnt Horizon (8.5-22.5 cm)			
Check	16-32	21.4	6.8
Below Shank	18-31	22.1	4.7
20 cm ⟶	16-28	21.1	4.6
B-C Horizon (22.5-27.5 cm)			
Check	24-38	31.3	5.8
Below Shank	23-34	28.1	3.3
20 cm ⟶	20-30	26.9	[illegible]
Csk Horizon (27.5-40 cm)			
Check	25-37	30.9	4.5
Below Shank	28-46	34.1	6.1
20 cm ⟶	21-38	28.1	6.1

[1] Seven replicates.

Table 20. Percent clay for samples taken from below shank, 20 cm ⟶, and check areas (South Field).

	Range[1]	Mean[2]	Standard Deviation
Ap Horizon (0-8.5 cm)			
Check	12-23	16.4a	4.5
Below Shank	15-26	19.3a	4.5
20 cm ⟶	23-21	16.6a	3.9
Bnt Horizon (8.5-22.5 cm)			
Check	14-30	24.0a	7.4
Below Shank	18-34	30.1b	5.8
20 cm ⟶	14-29	19.8a	6.0
B-C Horizon (22.5-27.5 cm)			
Check	30-39	33.6a	3.1
Below Shank	27-33	30.6a	1.9
20 cm ⟶	28-37	32.7a	3.7
Csk Horizon (27.5-40 cm)			
Check	30-38	33.0a	3.3
Below Shank	20-31	26.7b	4.6
20 cm ⟶	29-38	32.4a	3.5

[1] Seven replicates.

[2] Means not followed by the same letter within each depth are statistically different according to LSD test.

between treatments. Similar results are also found in the south field where available water percentages are quite close for all three treatments (Table 16). The increased clay content found in the 8.5-22.5 cm depth of the below shank area compared to the check and 20 cm $\longrightarrow$ areas does not cause a dramatic increase in available water percentage (Table 16).

4.6 DISCUSSION (PARTICLE SIZE DISTRIBUTION)

Strong evidence for the physical lifting of clay upwards in the profile is presented in the data from ripping done on wide shank spacing (112 cm). Clay appears to have been lifted from the lower two horizons and redeposited in the surface two horizons, with the most visible displacement being from the lowest (Csa) horizon to the second (Bnt) horizon. Concomitant with this upward movement of clay is a downward movement of sand in the below shank area Table 15). This could be explained by infilling of fine sand from surface horizons through fractions and large pores created by the shank disturbance. Clay levels in the 20 cm $\longrightarrow$ region behave similarily to those in the check region indicating that the influence of the shank is confined to a narrow region for this wide shank spacing.

Evidence for physical lifting of clay by ripping, with a narrow shank spacing (56 cm), in the North Field is lacking. If anything, the data suggests a slight downward movement of clay from the B-C horizon to the Csa horizon in the below shank region, although this is not statistically significant. One possible explanation for this discrepancy between the two fields (North and South) lies in soil

moisture conditions at the time of ripping. It is possible that ripping done on the North Field with the narrow shank spacing was carried out at a time when there was sufficient moisture in the profile to prevent the zone of shear plane development from extending into the lower horizons. Without the resultant cracking and fissuring of the clay enriched lower horizons, clods of subsurface material are not translocated upwards. Conversely, ripping in the South Field was probably done when moisture content was low enough throughout the profile to allow sufficient fracturing around the shank to move clods of clay enriched material upwards. As was pointed out in the literature review, soil conditions at the time of ripping greatly influence its effectiveness as an ameliorative tool (Cooper 1971, Trouse and Humbert 1959).

5. CONCLUSIONS

Ripping in the North Field with narrow shank spacings (56 cm) caused very little change in soil chemical properties (SAR, EC, pH). Deep plowing in the same field, using a single moldboard plow, increased pH and EC significantly in surface horizons and reduced SAR throughout the profile. Ripping done in the South Field with wide shank spacings (112 cm) caused noticeable increases in SAR, EC and pH in the two surface horizons in the below shank area. EC was also increased quite substantially in the lowest horizon of the 20 cm $\longrightarrow$ sampling location in the South Field.

Observed changes in soil chemical properties (SAR, EC, pH) in the below shank area of the South Field are attributed to both physical lifting of subsurface material upwards and capillary moisture movement. Increased SAR values are undesirable because of negative influences on soil structure and subsequent long-term melioration. Increases in EC and pH were of insufficient magnitude to cause any deleterious or positive effects.

Lack of evidence for the alteration of soil chemical properties in the disturbed ripping treatment areas (below shank and 20 cm $\longrightarrow$) in the North Field is explained as follows. Firstly, narrow shank spacings cause a greater degree of disruption making it difficult to identify the centre of the disturbed zone where the greatest degree of physical disruption and subsequent redistribution of salts by

moisture would occur. Secondly, it is possible that there was adequate moisture present in the soil profile at the time the ripping operation was carried out to cause plastic flow shear and prevent substantial shattering and mixing.

Results of the investigations into moisture distribution in ripped and unripped soil profiles of the South Field indicate greater moisture penetration between the 15 and 40 cm depths in the ripped profile. Moisture penetration after substantial rainfall is greatest in the area directly affected by the shank, termed the "below shank" area. Increased moisture is also found 20 cm to the side of the shank track to a depth of 25 cm. Moisture content in the unripped (check) profile did not increase below the 15 cm depth after substantial rainfall. The increased moisture present in the disturbed areas (below shank and 20 cm $\longrightarrow$) appears to have been used by the crop as evidenced by the increased crop height in these areas.

Particle size distribution throughout the profile is not changed by ripping in the North Field. The lack of horizon displacement in the profile would partially explain the absence of any change in chemical properties. Results from the South Field (wide shank spacing) indicate clay is moved upwards from the lowest (Csk) horizon to the second (Bnt) horizon. Concomitant with this upward movement of clay would be a redistribution of salt in the profile.

Detailed investigations into chemical and physical properties of Solonetzic soils four years after ripping have shown that this tillage has the ability to increase moisture penetration and alter soil chemical properties. The increased moisture would appear to aid

crop growth but also leads to changes in salt distribution which may be undesirable. By cracking the Bnt horizon and allowing moisture to percolate into the more saline subsoil, the potential for re-salinization of the surface horizons is being created.

6. REFERENCES

ABRAHAM, L. and BOSCKAI, J. 1971. The utilization and amelioration of Solonetzic soils in Hungary. pp. 61-97. In I. Szabolcs (ed.). European Solonetz soils and their reclamation. Akademiai Kiado, Budapest.

ALBERTA AGRICULTURE 1981. Management of Solonetzic soils. Agdex 516-8. 8 pp.

ALEKSANDRIAN, K. V. 1980. Machinery for the amelioration of salt-affected soils. pp. 134-141. In Proc. Intnl. Symp. on Salt Affected soils. Karnal.

ALLMARAS, R. R., RICKMAN, R. W., EKIN, L. G. and KIMBALL, B. A. 1977. Chiseling influences on soil hydraulic properties. Soil Sci. Soc. Am. Proc. 41: 796-803.

ALZUBAIDI, A. and WEBSTER, G. R. 1983. Ion pairs in a Solonetzic soil. Can. J. Soil Sci. 63: 479-484.

AMERICAN PUBLIC HEALTH ASSOCIATION. 1971. Standard methods for examination of water waste water. 13th Edition. pp. 334.

ANDERSON, D. W. and BALLANTYNE, A. K. 1982. Five years of soil analysis and yield data on deep plowed Solonetzic soils in Saskatchewan. pp. 133-142. In Solonetzic soils in Alberta, Alberta Solonetzic Soils Working Group Progress Report, March, 1982.

BALLANTYNE, A. K. 1983. Five years of soil analysis and yield data on deep-plowed Solonetzic soil. Can. J. Soil Sci. 63: 191-197.

BOCSKAI, J. 1974. Reclamation of Solonetz soils affecting the A and B horizons. pp. 57-63. In Trans. of the 10th Intnl. Congress of Soil Sci., Volume X, Moscow.

BOHN, H. L., McNEAL, B. L. and O'CONNOR. 1979. Soil Chemistry. John Wiley and Sons, Inc., New York.

BOWSER, W. E. and PETERS, T. W. 1951. Soil survey of the Red Deer sheet. Report No. 16. Alberta Soil Survey, Univ. of Alberta, Edmonton.

BOWSER, W. E., MILNE, R. A. and CAIRNS, R. A. 1962. Characteristics of the major soil groups in an area dominated by Solonetzic soils. Can. J. Soil Sci. 42: 165-179.

BOWSER, W. E. and CAIRNS, R. R. 1967. Some effects of deep plowing on a Solonetzic soil. Can. J. Soil Sci. 47: 239-244.

BRESLER, E., McNEAL, B. L. and CARTER, D. L. 1982. Saline and Sodic Soils - Principles - Dynamics - Modeling. Springer-Verlag, New York.

CAIRNS, R. R. 1962. Some effects of deep working on Solonetz soil. Can. J. Soil Sci. 42: 273-275.

CAIRNS, R. R. 1969. Canadian Solonetz soils and their reclamation. pp. 233-237. In Agrokemia es Talajtan Tom. 18. Supplementum.

CAIRNS, R. R. and SZABOLCS, I. 1973. Effects of sodium sulfate and sodium carbonate solutions on chemical and physical properties of a Chernozem soil. Can. J. Soil Sci. 53: 399-403.

CANADA SOIL SURVEY COMMITTEE. 1978. The Canadian system of soil classification. Can. Dept. Agric. Publ. 1646. Supply and Services Canada, Ottawa, Ontario. 164 pp.

CLAYTON, J. S., EHRLICH, W. A., CANN, D. B., DAY, J. H. and MARSHALL, I. B. 1977. Soils of Canada, Vol. I. Agric. Canada, Ottawa.

COOPER, A. W. 1971. Effects of tillage on soil compaction. pp. 315-364. In Compaction of Agricultural Soils. ASAE Monograph, Amer. Soc. Agr. Eng., St. Joseph, Michigan.

de SIGMOND, J. 1926. Contribution to the theory of the origin of alkali soils. Soil Sci. 21: 149-158.

DREVER, K. W. and WIENS, E. H. 1980. Equipment comparisons for deep plowing Solonetzic soils. Paper No. 80-409. Prairie Agric. Machinery Inst., Lethbridge, Alberta.

DULEY, F. L. 1957. Subsoiling in the great plains. J. Soil Water Conserv. 12: 71-74.

FRENKEL, H., GOERTZEN, J. O. and RHOADES, J. D. 1978. Effects of clay type and content, exchangeable sodium percentage and electrolyte concentration on clay dispersion and soil hydraulic conductivity. Soil Sci. Soc. Amer. J. 42: 32-39.

HADAS, A., WOLF, D. and MEIRSON, I. 1978. Tillage implements - soil structure relationships and their effects on crop stands. Soil Sci. Soc. Amer. J. 42: 632-637.

HAMILTON, W. N. 1971. Salt in east-central Alberta. Bull. No. 29. Research Council of Alberta, Edmonton.

HANKS, R. J. and THORP, F. C. 1956. Influence of tillage on intake and storage of water. J. Soil Water Conserv. 11: 140-141.

HARKER, D. B., WEBSTER, G. R. and CAIRNS, R. R. 1977. Factors contributing to crop response on a deep plowed Solonetzic soil. Can. J. Soil Sci. 57: 279-287.

HARRIS, S. A. and PIP, E. 1973. Molluscs as indicators of late and post-glacial climatic history in Alberta. Can. J. Zool. 51: 209-215.

HARRON, W. R. A. 1979. The effect of sodium on water movement in a Duagh-Malmo soil association. M.Sc. Thesis, Univ. of Alberta, Edmonton.

HAUSER, V. L. and TAYLOR, H. M. 1964. Evaluation of deep tillage treatments on a slowly permeable soil. Trans. Amer. Soc. Agr. Eng. 7(2): 134-136.

HENDERSON, H. D., ALMASSI, M., MALIK, A. A. AND MOJADDADI, Z. 1981. Deep tillage in the Beqa'a Valley, Lebanon. Trans. Amer. Soc. Agr. Eng. 28: 1466-1470.

HERMANS, J. C. 1982. Soil Conservation Supervisor, Alberta Agriculture, Edmonton. (pers. comm.).

HRASKO, J. 1971. Salt affected soils in Czechoslovakia and the problems of their utilization. pp. 49-60. In I. Szabolcs (ed.). European Solonetz soils and their reclamation. Akademiai Kiado, Budapest.

JOFFE, J. S. 1948. Pedology. Rutgers Univ. Press, New Brunswick, New Jersey.

KARKANIS, P. G. and CAIRNS, R. R. 1981. Some effects of deep plowing and fertilizing a Solonetzic soil under irrigation. Can. J. Soil Sci. 61: 157-160.

KOVDA, V. A. and SAMOILOVA, E. M. 1969. Some problems of soda salinity. pp0. 21-35. In Agrokemiai es Talajtan Tom. 18. Supplementum.

KNEELAND, ERNEST. 1983. Cooperating farmer, Halkirk, Alberta. (pers. comm.).

KRYZANOWSKI, LEONARD. 1983. Soils Specialist, Alberta Soil and Feed Testing Laboratory, Edmonton, Alberta. (pers. comm.).

LANDSBURG, S. 1981. The role of seasonal salt and water fluxes in the genesis of Solonetzic B horizons. M.Sc. Thesis, Univ. of Alberta, Edmonton.

LAVADO, R. S. and CAIRNS, R. R. 1980. Solonetzic soil properties and yields of wheat, oats and barley as affected by deep plowing and ripping. Soil Tillage Res. 1: 69-79.

LAZARUS, A. L., HILL, K. C. and LODGE, J. P. 1966. A new colorimetric microdetermination of sulfate ion. pp. 291-293. In Automation in Analytical Chemistry. Technicon Symposia, Mediad.

Le BRETON, E. G. 1971. Hydrogeology of the Red Deer area, Alberta. Research Council of Alberta Rept. 71-1.

MACLEAN, A. H. and PAWLUK, S. 1975. Soil genesis in relation to groundwater and soil moisture regimes near Vegreville, Alberta. J. Soil Sci. 26: 278-293.

McKEAGUE, J. A. (ed.) 1978. Manual on soil sampling and methods of analysis, 2nd edition. Prepared by the Subcommittee on Methods of Analysis, Canada Soil Survey Committee, Can. Soc. Soil Sci. 212 pp.

McNEAL, B. L. and COLEMAN, N. T. 1966a. Effect of solution composition on soil hydraulic conductivity. Soil Sci. Soc. Amer. Proc. 30: 308-312.

McNEAL, B. L. and COLEMAN, N. T. 1966b. Effect of solution composition on the swelling of extracted soil clays. Soil Sci. Soc. Amer. Proc. 30: 313-317.

MECH, S. J., HARNER, G. M., COX, L. M. and CARY, E. E. 1967. Soil profile modification by backhoe mixing and deep plowing. Trans. Amer. Soc. Agr. Eng. 10: 775-779.

MUSICK, J. T. and DUSEK, D. A. 1975. Deep tillage of graded-furrow-irrigated Pullman clay loam. Trans. Amer. Soc. Agr. Eng. 18: 263-269.

MUSICK, J. T., DUSEK, D. A. and SCHNEIDER, A. D. 1981. Deep tillage of irrigated Pullman clay loam - long-term evaluation. Trans. Amer. Soc. Agr. Eng. 28: 1515-1519.

NICHOLS, M. L. and REAVES, C. A. 1958. Soil reaction to subsoiling equipment. Agric. Eng. Vol. 39: 340-343.

OBREJANU, O. G., OPREA, S. V. and SANDU, G. 1970. Improvement of Solonetzes and Solonetzic soils in Europe. Soviet Soil Sci. Pochvovedeniye No. 7: 94-106.

PAGE, A. L., MILLER, R. H. and KEENEY, D. R. (eds.) 1982. Methods of Soil Analysis. Part 2. Number 9(2). Agronomy. Amer. Soc. Agron. Inc., Madison, Wisconsin. pp. 167-179.

PAK, K. P. 1971. Solonetzes of the European part of the USSR and their reclamation. pp. 139-149. In I. Szabolcs (ed.). European Solonetz soils and their reclamation. Akademiai Kiado, Budapest.

PAWLUK, S. 1978. Groundwater as related to Solonetzic soils. pp. 26-31. In J.A. Toogood and R.R. Cairns (eds.). Solonetzic soils technology and management in Alberta. Univ. Alberta Bull. B-78-1 (2nd ed.).

PAWLUK, S. and BAYROCK, L. A. 1969. Some characteristics and physical properties of Alberta tills. Res. Council Alberta Bull. 26.

PAWLUK, S. and DUMANSKI, J. 1969. Notes from the field tour held in conjunction with symposium. pp. 197-199. In S. Pawluk (ed.). Pedology and Quaternary Research. Alberta Inst. Pedology, Edmonton.

RASMUSSEN, W. W., MOORE, D. P. and ALBAN, L. A. 1972. Improvement of a Solonetzic (slick spot) soil of deep plowing, subsoiling and amendments. Soil Sci. Soc. Amer. Proc. 36: 137-142.

RASMUSSEN, W. W. and McNEAL, B. L. 1973. Predicting optimum depth of profile modification by deep plowing for improving Saline-Sodic soils. Soil Sci. Soc. Amer. Proc. 37: 432-437.

RICHARDS, L. A. 1965. Physical condition of water in soil. In C. A. Black (ed.). Methods of soil analysis, Part 1. Agron. 9: 128-152. Am. Soc. Agron., Madison, Wisconsin.

SANDBORN, P. T. 1981. Dynamics of a Chernozemic soil system. M.Sc. Thesis, Univ. of Alberta, Edmonton.

SAVESON, I. L. and LUND, Z. F. 1958. Deep tillage for crop production. Trans. Amer. Soc. Agr. Eng. 2: 40-42.

STALKER, A. M. S. 1960. Surficial geology of the Red Deer-Stetler map area, Alberta. Memoir 306, Geological Survey of Canada.

SPAIN, J. M. and McCURE, D. L. 1956. Something new in subsoiling. Agron. Jr. 48: 192-193.

SZABOLCS, I. 1971. Solonetz soils in Europe, their formation and properties with particular regard to utilization. pp. 9-33. In I. Szabolcs (ed.). European Solonetz soils and their reclamation. Akademiai Kiado, Budapest.

SZABOLCS, I. 1979. Soil salinization and alkalization processes. Agrokemia es Talajtan Tom. 28. Supplementum. pp. 11-32.

SZABOLCS, I. and V. LESTAK. 1967. Capillary movement of sodium salt solutions in soil columns. Sov. Soil Sci. 1967(1) 483-488.

TROUSE, A. C. and HUMBERT, R. P. 1959. Deep tillage in Hawaii: 1. Subsoiling. Soil Sci. 88: 150-158.

TYURIN, I. V., ANTIPOV-KARATA, I. N. and CHIZHERSKII, M. G. (eds.). 1967. Reclamation of Solonetz soils in the USSR. Israel program for scientific translations, Jerusalem.

WELLS, RUSS. 1985. Research Officer, Alberta Research Council. (pers. comm.).

WELLS, R. E. and NIKIFORUK, L. 1984. Soil survey of the County of Paintearth - progress report. Terrain Sciences Dept., Alberta Research Council, Edmonton.

WELLS, R. E. and HERMANS, J. C. 1985. Use of color infrared aerial photography for mapping solonetzic soils in east-central Alberta. Open file report No. 1985-19, Terrain Sciences Dept., Alberta Research Council, Edmonton. 37 pp.

WHITE, E. M., GARTNER, F. R. and BUTTERFIELD, R. 1981. Range claypan soil improvement: response from furrowing and ripping in northwestern South Dakota. Journal of Range Management 34(2): 119-125.

ZALIK, SAUL. 1981. Outline of Statistical Methods for Biological and Medical Research. Dept. of Plant Science, Univ. of Alberta, Edmonton. pp. 106-112.

APPENDIX

Appendix 1A. Soluble ions, electrical conductivity and saturation percentage for saturation extracts (Ripping - North Field).

Rep.	Treatment	Depth (cm)	Ca^{++}*	Na^{+}	Mg^{++}	K^{+}	$SO_4^{=}$	HCO_3^{-}	E.C.**	Sat. %
1	Check	0- 9	1.8	7.3	0.7	0.1	5.1	2.3	0.9	41
		9-12	1.2	10.9	0.6	0.06	6.4	4.4	1.0	37
		12-20	1.8	21.5	0.6	0.02	11.3	8.8	2.0	60
		20-25	2.4	25.5	1.5	0.03	15.5	8.8	2.0	60
		25-34	7.9	60.3	4.3	0.1	57.5	6.9	4.7	65
1	Below Shank	0- 9	2.6	6.0	1.0	0.05	1.9	7.9	0.7	40
		9-12	3.8	11.1	1.0	0.03	2.4	10.4	1.0	39
		12-20	2.8	14.2	0.8	0.02	3.8	11.9	1.2	45
		20-25	2.2	18.6	0.7	0.1	7.2	11.3	1.4	45
		25-34	2.38	30.7	1.0	0.05	16.6	7.0	2.6	71
1	20 $\longrightarrow$	0- 9	7.9	5.67	3.0	0.3	4.6	11.2	1.2	43
		9-12	2.3	8.37	0.8	0.1	5.2	7.4	0.9	40
		12-20	2.1	17.7	0.7	0.01	6.9	10.6	1.4	--
		20-25	2.6	20.7	1.3	0.04	13.6	8.0	1.7	54
		25-34	4.1	35.4	2.6	0.06	33.9	7.6	3.2	62
2	Check	0-10	1.8	7.7	0.2	0.1	5.6	3.0	0.8	36
		10-17	1.6	25.5	0.5	0.1	11.4	9.6	1.4	54
		17-23	3.8	24.8	1.2	0.03	10.4	13.6	1.9	64
		23-36	27.2	74.1	11.5	0.4	97.5	8.9	6.9	50

(continued)

Appendix 1A. (continued).

Rep.	Treatment	Depth (cm)	Ca^{++}*	Na^{+}	Mg^{++}	K^{+}	$SO_4^{=}$	HCO_3^{-}	E.C.**	Sat. %
2	Below Shank	0-10	2.2	14.2	0.8	0.1	4.0	12.5	1.3	40
		10-17	3.8	30.8	1.4	0.06	12.8	26.0	2.4	54
		17-23	5.6	30.0	1.8	0.1	16.1	14.0	2.5	74
		23-36	4.8	32.4	1.9	0.2	18.1	12.5	2.4	72
2	20 ⟶	0-10	3.6	13.2	1.0	0.1	3.0	12.9	1.3	38
		10-17	2.8	22.3	0.5	0.06	12.1	9.4	1.8	44
		17-23	3.6	26.7	1.2	0.07	15.9	10.9	2.2	--
		23-36	28.4	75.7	13.7	0.4	89.0	7.3	7.2	54
3	Check	0- 9	0.9	7.6	0.4	0.1	6.6	1.5	0.8	37
		9-19	1.8	20.7	0.5	0.04	6.7	13.7	1.8	--
		19-29	4.0	33.6	1.4	0.06	18.4	12.1	2.3	63
		29-38	3.8	24.2	0.9	0.07	12.0	9.2	1.7	113
3	Below Shank	0- 9	1.3	4.3	0.01	0.1	3.2	1.4	0.5	35
		9-19	0.7	11.8	0.2	0.04	5.7	5.0	1.0	38
		19-29	1.8	31.6	0.6	0.07	13.8	15.0	2.3	52
		29-38	2.0	36.6	0.9	0.07	26.5	9.3	2.9	71
3	20 ⟶	0- 9	2.6	7.9	0.4	0.2	6.0	4.8	0.7	35
		9-19	0.6	6.6	0.2	0.09	3.3	3.0	0.5	26
		19-29	0.9	20.4	0.4	0.04	11.8	7.0	1.7	46
		29-38	1.9	32.4	1.1	0.07	18.5	10.8	2.4	65

(continued)

Appendix 1A. (continued).

Rep.	Treatment	Depth (cm)	Ca^{++}*	Na^{+}	Mg^{++}	K^{+}	$SO_4^{=}$	HCO_3^{-}	E.C.**	Sat. %
4	Check	0- 8	0.9	2.9	0.5	0.2	1.7	2.4	0.4	39
		8-16	0.4	1.7	0.7	0.06	1.6	1.0	0.3	34
		16-28	2.2	16.5	0.6	0.02	2.9	14.3	1.2	49
		28-40	1.2	12.3	0.2	0.02	4.7	6.6	0.9	84
4	Below Shank	0- 8	1.7	5.7	0.5	0.2	2.8	4.6	0.6	38
		8-16	2.1	13.1	0.5	0.05	2.3	12.0	1.1	38
		16-28	3.5	18.5	0.9	0.03	5.4	12.8	1.4	57
		28-40	3.1	22.5	1.0	0.1	14.6	8.1	1.8	82
4	20 ⟶	0- 8	1.5	4.1	0.02	0.2	2.1	2.6	0.5	36
		8-16	1.2	7.8	0.4	0.07	2.6	6.0	0.6	35
		16-28	16.3	46.9	4.5	0.1	58.0	10.1	4.7	47
		28-40	8.0	39.2	2.8	0.2	40.1	9.0	3.6	72
5	Check	0- 7	1.4	4.7	0.03	0.08	2.8	2.4	0.6	33
		7-15	0.7	--	0.3	0.001	--	6.6	0.5	34
		15-26	2.5	15.0	0.9	0.07	5.8	10.4	1.3	48
		26-40	1.2	12.3	0.5	0.01	4.7	6.4	1.0	59
5	Below Shank	0- 7	1.7	2.9	0.7	0.2	1.0	4.2	0.5	37
		7-15	1.0	--	0.4	0.02	--	4.8	0.2	33
		15-26	2.9	2.3	1.0	0.04	0.5	5.3	0.4	51
		26-40	3.0	2.5	0.5	0.06	0.7	4.8	0.4	47

(continued)

Appendix 1A. (continued).

Rep.	Treatment	Depth (cm)	Ca^{++}*	Na^{+}	Mg^{++}	K^{+}	$SO_4^{=}$	HCO_3^{-}	E.C.**	Sat. %
5	20 ⟶	0- 7	2.2	2.3	0.5	0.2	1.2	2.8	0.4	37
		7-15	0.8	1.7	0.2	0.07	0.8	1.6	0.2	36
		15-26	3.6	3.2	0.9	0.05	0.6	6.8	0.5	47
		26-40	2.4	3.0	1.0	0.05	0.4	4.8	0.3	54
6	Check	0- 9	4.2	--	1.8	0.2	--	5.7	1.2	44
		9-20	2.8	--	1.0	0.03	--	7.2	1.5	37
		20-37	3.9	25.7	1.7	0.1	11.0	15.1	--	--
		37-48	1.1	13.3	0.4	0.02	7.9	5.0	1.0	117
6	Below Shank	0- 9	4.4	12.1	1.4	0.2	3.0	14.8	1.3	42
		9-20	2.6	16.8	1.0	0.03	7.0	10.4	1.2	48
		20-37	3.5	26.3	1.3	0.1	18.6	8.8	2.0	69
		37-48	2.2	84.7	13.0	0.1	100.0	7.2	7.4	56
6	20 ⟶	0- 9	5.0	16.0	1.6	0.2	3.8	16.4	1.6	44
		9-20	3.4	20.0	0.8	0.05	8.6	11.6	1.6	47
		20-37	6.9	27.4	1.0	2.9	33.9	7.4	2.0	101
		37-48	24.7	72.1	9.7	0.04	94.3	5.7	6.6	76
7	Check	0- 6	1.8	12.5	0.7	0.08	3.2	10.5	1.1	39
		6-15	1.7	14.4	0.4	0.06	4.7	10.0	1.1	38
		15-23	1.9	17.9	0.5	0.1	8.4	8.4	1.4	54
		23-36	1.5	22.4	0.6	0.01	18.1	5.1	1.8	73

(continued)

Appendix 1A. (continued).

Rep.	Treatment	Depth (cm)	Ca^{++}*	Na^{+}	Mg^{++}	K^{+}	$SO_4^{=}$	HCO_3^{-}	E.C.**	Sat. %
7	Below Shank	0- 6	4.3	23.3	1.1	0.1	7.2	16.0	2.0	43
		6-15	3.7	29.7	1.3	0.09	27.1	4.5	2.6	107
		15-23	13.7	46.0	2.1	0.03	38.8	10.7	3.6	58
		23-36	25.2	77.6	8.2	0.2	98.2	5.9	6.8	119
7	20 ⟶	0- 6	2.8	21.6	1.5	0.1	10.0	11.9	1.7	42
		6-15	3.4	37.8	1.3	0.1	18.0	17.8	3.0	42
		15-23	21.0	72.1	5.6	0.09	93.6	5.8	6.9	53
		23-36	61.6	72.1	10.6	0.1	102.4	5.2	6.4	115

* Ion concentrations expressed in meq/l.
** EC expressed in mS/cm.

Appendix 1B. Soluble ions, electrical conductivity and saturation percentage for saturation extracts (Ripping - South Field).

Rep.	Treatment	Depth (cm)	Ca^{++}*	Na^{+}	Mg^{++}	K^{+}	$SO_4^{=}$	HCO_3^{-}	E.C.**	Sat. %
1	Check	0-10	2.3	11.3	0.4	0.2	7.4	4.5	1.1	33
		10-20	1.0	17.2	0.4	0.02	10.0	7.3	1.5	44
		20-30	3.7	21.6	0.9	0.007	10.4	11.2	1.8	63
		30-40	4.7	24.1	1.5	0.04	11.6	12.4	2.0	67
1	Below Shank	0-10	2.2	15.3	0.6	0.08	8.1	7.8	1.5	36
		10-20	3.2	30.6	1.0	0.04	9.1	18.5	2.2	53
		20-30	4.0	20.4	0.8	0.005	9.3	10.2	1.6	65
		30-40	2.8	22.5	0.8	0.03	12.2	9.4	1.8	78
1	20 ⟶	0-10	2.9	16.4	1.1	0.2	6.6	12.0	1.6	34
		10-20	0.9	16.8	0.3	0.02	10.2	3.4	1.3	37
		20-30	4.4	24.6	1.8	0.02	10.2	12.5	1.7	66
		30-40	18.9	61.1	5.1	0.1	70.3	7.4	5.4	70
2	Check	0- 8	2.6	8.6	0.7	0.1	4.1	6.1	0.9	39
		8-17	1.4	9.3	0.3	0.08	7.3	3.8	0.9	31
		17-32	2.4	20.5	0.8	0.02	6.3	14.5	1.6	71
		32-42	26.7	59.5	11.8	0.3	70.9	6.6	6.3	70
2	Below Shank	0- 8	4.4	13.9	1.3	0.2	2.7	14.2	1.4	36
		8-17	2.4	21.0	0.7	0.07	7.2	11.9	1.6	65
		17-32	3.0	22.9	1.3	0.05	10.9	12.6	1.9	81
		32-42	2.5	22.7	0.8	0.08	14.9	7.4	1.7	88

(continued)

Appendix 1B. (continued).

Rep.	Treatment	Depth (cm)	Ca^{++}*	Na^{+}	Mg^{++}	K^{+}	$SO_4^{=}$	HCO_3^{-}	E.C.**	Sat. %
2	20 ⟶	0- 8	5.6	9.8	2.0	0.2	2.6	12.4	1.3	38
		8-17	2.3	14.4	0.3	0.1	9.4	7.4	1.4	39
		17-32	2.7	22.2	1.0	0.01	10.3	10.7	1.6	76
		32-42	6.6	39.6	3.1	0.1	39.0	7.3	3.4	68
3	Check	0- 8	1.6	6.0	0.04	0.1	4.7	1.9	0.6	31
		8-20	1.7	23.8	0.5	0.1	8.2	14.7	1.8	51
		20-31	3.8	28.1	1.2	0.08	18.1	9.5	2.3	58
		31-41	29.0	74.1	12.1	0.4	99.6	7.0	7.2	57
3	Below Shank	0- 8	5.0	18.1	1.9	0.3	5.6	17.4	1.8	35
		8-20	2.5	23.1	0.8	0.1	6.4	27.4	1.6	49
		20-31	3.6	27.1	0.9	0.09	11.4	13.3	2.1	62
		31-41	7.0	39.1	3.3	0.3	41.7	6.6	3.4	58
3	20 ⟶	0- 8	3.3	13.5	1.1	0.2	6.1	8.4	1.2	32
		8-20	3.6	21.9	0.7	0.06	7.2	15.0	1.8	53
		20-31	2.9	23.0	1.1	0.09	13.1	8.9	1.9	63
		31-41	27.1	73.7	12.4	0.5	93.6	7.5	6.6	53
4	Check	0- 9	1.1	7.6	0.04	0.09	6.0	0.81	0.9	33
		9-21	2.0	27.1	0.6	0.2	10.6	14.4	2.0	60
		21-30	5.2	25.9	1.9	0.05	15.9	12.6	2.4	70
		30-40	4.5	37.4	2.0	0.1	22.4	10.5	2.7	76

(continued)

Appendix 1B. (continued).

Rep.	Treatment	Depth (cm)	Ca^{++}*	Na^{+}	Mg^{++}	K^{+}	$SO_4^{=}$	HCO_3^{-}	E.C.**	Sat. %
4	Below Shank	0- 9	4.5	31.1	1.9	0.2	6.1	26.8	2.6	30
		9-21	2.6	33.7	0.8	0.04	10.4	17.2	2.2	48
		21-30	3.0	24.2	1.1	0.03	12.4	11.0	2.0	65
		30-40	5.7	47.7	2.4	0.2	31.2	12.9	3.5	65
4	20 ⟶	0- 9	2.4	14.0	0.7	0.2	7.2	5.8	1.5	35
		9-21	2.1	36.5	0.8	0.02	13.2	16.0	2.4	46
		21-30	6.9	40.4	2.7	0.05	26.7	12.6	3.2	70
		30-40	12.6	70.9	4.0	0.3	65.9	15.9	5.6	58
5	Check	0- 6	1.0	10.2	0.3	0.1	3.5	5.6	1.2	36
		6-13	1.2	20.3	0.4	0.1	15.8	3.4	1.8	34
		13-21	3.3	31.5	1.2	0.02	14.4	13.8	2.3	62
		21-40	18.8	70.9	7.7	0.2	80.4	8.3	6.0	62
5	Below Shank	0- 6	2.5	14.7	0.9	0.08	3.5	9.5	1.8	43
		6-13	3.2	18.5	1.4	0.07	14.8	14.9	2.3	--
		13-21	2.4	30.9	1.1	0.03	16.5	10.7	2.4	58
		21-40	12.8	47.3	5.6	0.2	57.0	7.1	4.5	61
5	20 ⟶	0- 6	4.3	25.0	1.7	0.1	9.5	16.5	2.3	29
		6-13	2.0	21.1	0.9	0.07	11.6	7.3	1.9	36
		13-21	4.8	31.2	1.8	0.03	18.2	12.9	2.5	57
		21-40	18.2	67.0	7.9	0.2	82.0	7.2	6.1	57
6	Check	0- 5	0.9	8.5	0.4	0.2	7.5	1.1	1.0	33
		5-10	0.4	9.6	2.0	0.04	7.9	1.3	1.0	35
		10-23	1.5	23.2	0.5	0.07	11.8	9.5	1.8	64
		23-36	5.9	30.0	2.5	0.02	17.9	10.8	2.3	67

(continued)

Appendix 1B. (continued).

Rep.	Treatment	Depth (cm)	Ca^{++}*	Na^{+}	Mg^{++}	K^{+}	$SO_4^{=}$	HCO_3^{-}	E.C.**	Sat. %
6	Below Shank	0- 5	1.6	15.5	0.7	0.1	9.0	5.9	1.6	43
		5-10	1.3	18.7	0.7	0.03	9.5	6.2	1.5	41
		10-23	2.0	25.0	0.8	0.05	13.2	10.6	1.8	46
		23-36	1.9	24.1	0.7	0.02	17.9	10.8	1.8	74
6	20 ⟶	0- 5	1.8	16.7	0.9	0.3	11.5	3.1	1.5	37
		5-10	0.4	8.8	0.2	0.1	7.2	1.5	0.8	31
		10-23	2.1	27.1	0.8	0.02	10.3	15.5	2.0	58
		23-36	6.8	38.3	2.6	0.03	23.0	12.0	2.8	66
7	Check	0-11	0.7	6.5	0.3	0.1	4.0	1.2	0.7	36
		11-19	2.7	13.5	1.0	0.04	6.4	7.1	1.1	67
		19-28	2.7	13.5	1.0	0.04	6.4	7.1	1.1	67
		28-38	3.2	22.4	1.2	0.007	10.8	10.1	1.6	68
7	Below Shank	0-11	2.1	14.4	0.6	0.1	3.8	12.1	1.0	46
		11-19	1.5	17.1	0.4	0.007	4.3	13.0	1.3	67
		19-28	1.5	17.1	0.4	0.007	4.3	13.0	1.3	67
		28-38	--	--	--	--	--	--	--	--
7	20 ⟶	0-11	0.8	10.7	0.3	0.1	6.9	3.1	0.9	35
		11-19	3.3	21.7	1.5	0.07	10.0	13.0	--	--
		19-28	3.3	21.7	1.5	0.07	10.0	13.0	--	--
		28-38	13.2	55.6	5.9	0.07	60.5	6.8	4.6	56

* Ion concentrations expressed in meq/l.
** EC expressed in mS/cm.

Appendix 1C. Soluble ions, electrical conductivity and saturation percentage for saturation extracts (Deep Plowing - North Field).

Rep.	Treatment	Depth (cm)	Ca^{++}*	Na^{+}	Mg^{++}	K^{+}	$SO_4^{=}$	HCO_3^{-}	E.C.**	Sat. %
1	Deep Plow	0- 9	5.5	4.3	1.6	0.20	1.0	9.6	0.9	43
		9-20	3.2	11.8	1.2	0.07	1.9	12.0	1.2	40
		20-25	2.5	15.7	1.0	0.10	2.6	14.8	1.5	52
		25-34	3.0	17.9	1.4	0.20	6.2	12.9	2.1	61
2	Deep Plow	0-10	4.7	12.4	1.3	0.30	3.2	14.6	1.4	47
		10-17	4.0	16.6	1.5	0.07	5.3	15.3	1.4	47
		17-23	4.3	23.4	1.8	0.07	13.9	6.1	2.3	47
		23-36	25.7	52.4	8.5	0.20	88.2	9.0	7.5	51
3	Deep Plow	0- 9	4.6	9.6	1.4	0.20	3.4	10.9	1.2	60
		9-19	6.9	18.8	2.7	0.10	17.0	7.7	2.2	88
		19-29	16.2	21.7	6.6	0.10	46.3	9.6	4.4	56
		29-38	13.9	24.1	6.0	0.20	47.5	7.7	4.5	47
4	Deep Plow	0- 8	4.1	12.7	1.2	0.20	3.1	13.6	1.4	55
		8-16	5.5	17.9	1.8	0.06	10.0	11.8	1.9	62
		16-28	8.4	27.7	3.4	0.10	23.6	9.6	3.0	63
		28-40	25.8	31.2	8.5	0.20	68.8	6.5	5.7	64
5	Deep Plow	0- 7	4.0	9.6	1.3	0.20	1.3	13.0	1.1	47
		7-15	3.0	12.0	0.8	0.04	2.2	11.4	1.7	50
		15-26	4.0	19.3	1.3	0.03	6.4	13.3	1.8	55
		26-40	26.1	37.8	8.1	0.40	74.7	8.0	6.3	51

Appendix 1C. (continued).

Rep.	Treatment	Depth (cm)	Ca^{++}*	Na^{+}	Mg^{++}	K^{+}	$SO_4^{=}$	HCO_3^{-}	E.C.**	Sat. %
6	Deep Plow	0- 9	3.5	10.8	1.0	0.10	1.9	12.2	1.1	44
		9-20	16.9	25.1	4.8	0.10	36.5	6.7	3.4	57
		20-37	4.5	20.4	1.2	0.03	11.2	11.5	1.9	54
		37-48	14.6	33.5	5.2	0.10	48.9	12.6	5.0	47
7	Deep Plow	0- 6	3.4	10.1	0.9	0.10	1.8	12.9	1.2	45
		6-15	3.4	14.6	0.7	0.02	3.5	12.4	1.4	49
		15-23	3.6	24.2	1.3	0.03	8.3	16.4	2.2	48
		23-36	27.8	43.0	7.6	0.40	82.5	6.7	6.6	50

* Ion concentrations expressed in meq/l.
** EC expressed in mS/cm.